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ORIGINAL ARTICLES.

Domes in Scotland and South Africa: Arran and Vredefort.

By E. B. Bailey, M.C., B.A.

HALL and Molengraaff have recently produced a memoir of outstanding importance dealing with the Vredefort Mountain Land on the border of the Transvaal and the Orange Free State (1925). Their account, which is a model of lucidity, is accompanied by a map and sections, and is copiously illustrated with photographs, mainly of rock slices. It includes a chapter on the History of Research, and another that introduces tectonic comparisons with the Black Hills of Dakota and Wyoming and the Ries Kessel near Nördlingen. The features of the Vredefort district that command most attention in this country are its tectonics and its flinty crush-rocks, or pseudotachylytes, to use Shand's alternative designation. Hall and Molengraaff's memoir supplies much new information on these two subjects, and also in regard to other topics, stratigraphical and petrographical, that are of rather more local interest. In the present notice, only one aspect of the memoir will be discussed, namely the tectonics of the Vredefort Dome.

The Vredefort Dome is the most wonderful of its kind known in the world. It is of great dimensions and almost perfect symmetry; and the tilted sediments on its flanks have been carried through the vertical and overturned, so that from all sides they dip inwards towards the centre. It is a gigantic mushroom. Other mushrooms have lived for a day in tectonic literature, as for instance in the interpretation of the Brèche Klippe of the Pre-Alps. The Vredefort mushroom will live for ever: it is definitely rooted in this memoir. It has to be accounted for; it cannot be explained away.

Two possibilities are considered by Hall and Molengraaff in explanation of the Vredefort Dome. The one is *centripetal pressure*, which, as they point out, has already been invoked in this connexion by Jorissen in 1906 and Sandberg in 1907. The other is *magmatic upheaval*. The conditions of the problem will presently be summarized in some detail—here we need only warn the reader that there is good reason to accept Hall and Molengraaff's conclusion that the Vredefort Granite is in the main older than the tilted sediments around it. This in itself does not preclude a hypothesis of igneous updoming. The two authors think, however, that the balance of evidence favours the alternative conception of centripetal pressure.

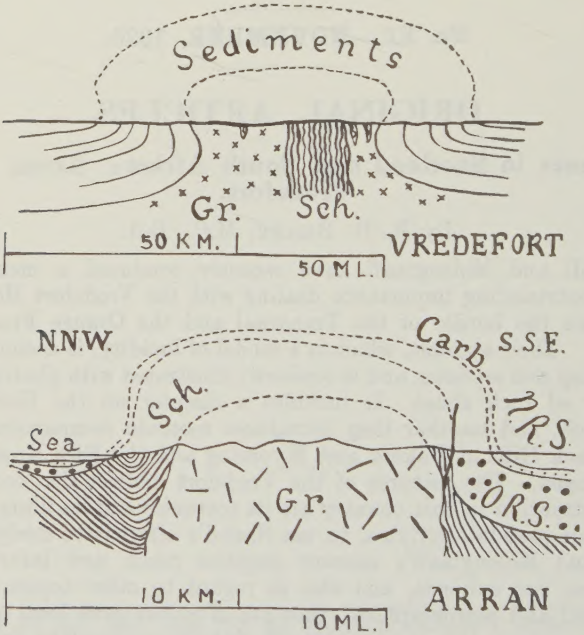

FIG. 1.—Sections across Vredefort and Arran Domes. *Vredefort.*—Later Sediments domed over Older Granite and Schists, after A. L. Hall and G. A. F. Molengraaff (1925, Fig. 20, p. 149). If I were redrawing this section, I should show Newer Magma occupying the centre of the dome a little below the surface. *Arran.*—New Red Sandstone, Carboniferous, Old Red Sandstone, and Schists domed by Tertiary Granite.

I venture to take up arms in defence of the idea of magmatic upheaval for the following reasons :—

(1) The capacity of magma to cause domal upheaval was clearly established by Gilbert in his 1877 *Report on the Geology of the Henry Mountains.* Since then, many other illustrations of this power have been described, mostly from America, as may be gathered from an inspection of text-books such as Harker's or Daly's. In our own country, the best examples are to be found in Arran (one of them dealt with in this paper) and at Traprain Law in East Lothian (1910*a*, p. 98).

(2) Recent work has rendered it unnecessary to suppose an undisturbed base of laccolithic habit to every intrusion that domes its roof. Such an intrusion may occupy a pipe ; and the latter, supposing it has not been opened by explosion or absorption, may have originated through foundering of country rock. In some cases, the foundering may have taken place piecemeal as in Daly's well-known conception of stoping (1903*b*). In others, it may have proceeded *en masse* within a ring-fracture, as has been suggested by analogy with the superficial cauldron subsidence of Glen Coe (1909, p. 669).

(3) The possibility of a magma uplifting its roof has received a novel confirmation in Skye and Mull. In the former island, Harker distinguished a group of Inclined Sheets dipping steeply towards the igneous centre. He thought that they probably did not extend very far downwards, and attributed their disposition to stresses formed during domal upheaval (1904, pp. 366, 369, 427, 428). Later W. B. Wright and I found similar centrally inclined sheets developed in profusion in Mull. The name Cone-Sheets has been adopted for them, and we picture them as constituting a complex that more or less resembles an umbrella blown inside out and directed upwards to the heavens. Anderson has discussed the mechanics of cone-sheet intrusion. He regards cone-sheets as the infillings of fissures developed at the top of a magma-filled pipe, where the magma, under excess of pressure, tends to raise its roof by fracture rather than flexure (1924, p. 11). As the cone-sheet complexes of Mull have an aggregate thickness of some thousands of feet, the central elevation attendant upon their intrusion is comparable with that produced at Arran, where the country rock has preferred to bend instead of breaking.

(4) Hall and Molengraaff demonstrate the existence of a comparatively late subterranean intrusion under part of the Vredefort Dome. Their descriptions give good cause to suspect that magma of the required date also underlies the whole outcrop of the Vredefort Granite.

(5) Hall and Molengraaff say, " Given the requisite energy it is not difficult to see that an upward pressing magma using a relatively passive roof of Vredefort Granite as a kind of buffer, could raise, bend up, and finally tilt a considerable thickness of overlying sediments, but it is very difficult to realize how actual *overtilting* could be thus brought about on the observed scale " (1925, p. 161). It may, however, be pointed out that it is impossible to communicate an upward push through a plastic column without at the same time developing a centrifugal push. If the upward push raises the overlying rocks, the outward push (at any fixed point) will steadily increase. It will also produce outward deformation, if this deformation can be accommodated by being indirectly communicated upwards so as to find relief in the raising of the roof. Subterranean outward deformation will laterally extend the superficial dome and ameliorate its slopes.

(6) A hypothesis of magmatic upheaval and concomitant centrifugal pressure, seems much more applicable at Vredefort than one of centripetal pressure. The movements are so intense and yet so symmetrical and local. There is no mountain movement in South Africa that can possibly be brought into the same period as that which saw the Vredefort Dome upheaved. On the other hand, Hall and Molengraaff themselves suggest that the Vredefort Dome may be of much the same age as its companion marvel, the Bushveld Complex—an igneous phenomenon (1925, p. 169).

(7) I should not have ventured to offer the above remarks were it not for striking analogies presented by the North Arran Dome. This structure is on a smaller scale than the Vredefort Dome, but the difference is not sufficient to make comparison futile. Its features have been deciphered by Gunn of the Geological Survey, and have long been before the public (1901, 1903, 1910). It is a curious fact, however, that Gunn knew almost everything about the subject except its interest for other people. He was a skilled stratigrapher who, towards the end of his life, met with, and solved, one of the most fascinating problems of igneous geology —the granite-propelled upheaval of North Arran. He seems to have thought that such phenomena might be expected anywhere in connexion with an igneous complex: his conclusions in regard to the upheaval can only be extracted as disconnected sentences scattered through his memoir; and he does not refer to the subject at all in enumerating the "principal additions to our knowledge of the geology of Arran made during the progress of the survey".[1]

With this introduction nothing more is required than brief summaries of what is known and conjectured regarding the domes of Arran and Vredefort.

ARRAN.

1. The granite complex of North Arran has a diameter of 8 miles, and is almost completely surrounded by pre-Devonian Schists. Within the complex, there are two granites that differ in no important particular except texture. The finer granite occupies an irregular interior position. It is described as intrusive into the coarser granite. Its outcrop has been determined, but not its three dimentional shape. The coarser outer granite has a very smooth

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[1] Since sending in this paper, my attention has been drawn to A. Geikie's introduction to *The Book of Arran* (edited by J. A. Balfour, published by Arran Soc., Glasgow, vol. i, 1910, pp. 22, 23). He emphasises the "gigantic force" with "which the schists and Old Red Sandstone have been driven aside to make way for" the granite of North Arran. The granite "may", he adds, "have borne upwards a huge blister-like envelope of Triassic strata, like one of Mr. Gilbert's laccolites in the Henry Mountains." For my own part, I think that the displacement of even the schists and Old Red Sandstone has been upward rather than outward, but this is a comparatively small difference of interpretation. Geikie's remarks are, of course, based upon Gunn's publications.

steep junction against the surrounding rocks. These latter, where they consist of Schists, are veined and metamorphosed by the

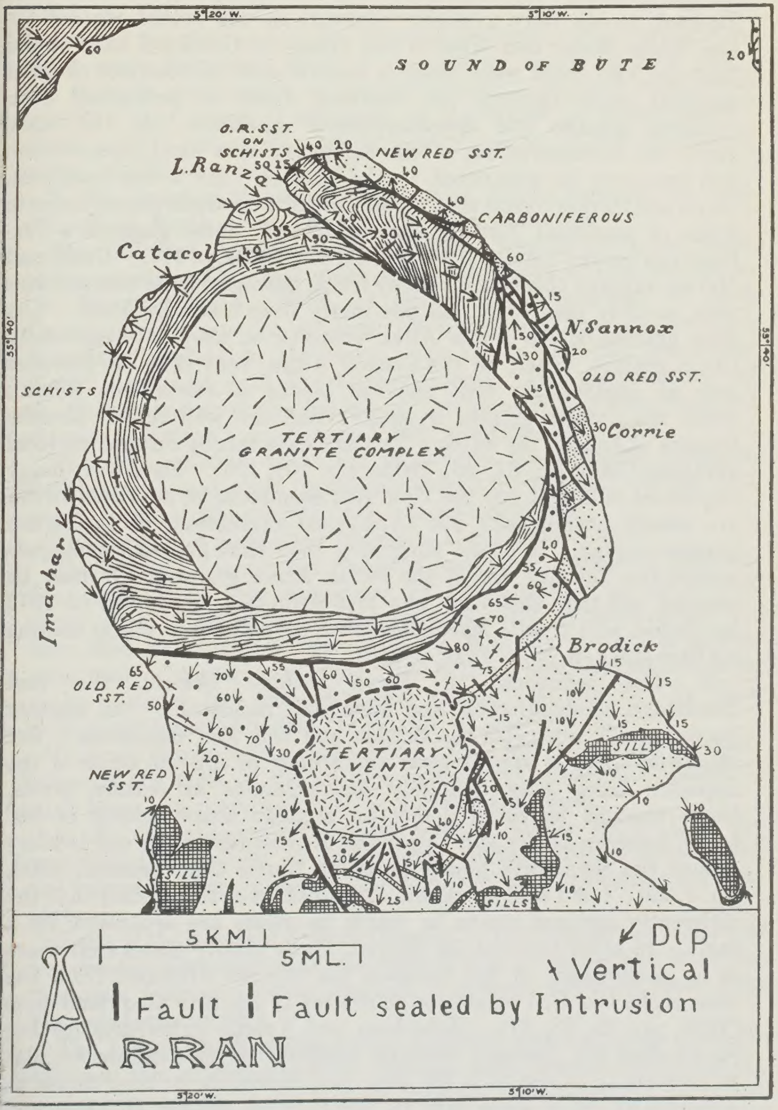

FIG. 2.—Map of Arran Domes (of which only the more northerly is dealt with in this paper). Schists, Old Red Sandstone, Carboniferous, and New Red Sandstone upheaved by Tertiary intrusions. Dykes omitted. After W. Gunn (1901, 1910) with minor alterations by the author.

granite. Along a comparatively small part of its circumference, the granite is bounded by Old Red Sandstone which it definitely metamorphoses. No veins have been noticed cutting the sandstone. Instead, at the only available exposure of the actual contact (in the White Water due West of the village of Corrie), I have found that the two rocks meet along a narrow zone of compact sheared material made through the breaking down of previously consolidated granite and metamorphosed sandstone. At the same time, the metamorphism of the sandstone is a local phenomenon and can only be attributed to the granite. At a few localities, Gunn and Harker record that the granite also metamorphoses dolerite dykes of presumed Tertiary date, which, of course, suggests a Tertiary age for the granite (1903, pp. 86, 87 ; 1903*a*, p. 117). Gunn and Harker support this conclusion by citing petrographical comparisons that, as they point out, had previously been made by Teall. The finer granite of the North Arran complex is, they say, extremely like a granite, which, in the Central Arran Vent (Fig. 2), intrudes into an agglomerate that encloses blocks of Cretaceous Chalk ; while the coarser granite is equally like the well-known Mourne Granite of Ireland for which a Tertiary date can be claimed on local evidence (1903, pp. 87, 90; 1903*a*, pp. 104, 105). Moreover, many important sills that cut the New Red Sandstone of southern Arran are clearly nothing else but hypabyssal expressions of the Arran granite-magma. It is not surprising then that Scottish geologists accept the Tertiary age of the North Arran granites. It may be pointed out that this view was first definitely advocated in 1873 by Geikie, who credits Macculloch with several observations leading up to it (1873, p. 305 ; 1897, p. 418).

2. The sediments of Arran include Schists, Old Red Sandstone, Carboniferous, and New Red Sandstone. An angular unconformity separates the Schists and Old Red Sandstone ; but otherwise there is approximate conformity of dip—in spite of the sequence being very definitely discontinuous at certain levels. Gunn thought he could detect an angular unconformity of 20° to 30° between Lower and Upper Old Red Sandstone at one locality (above the shepherd's house, north of North Glen Sannox, 1903, pp. 8, 29) ; but I find on careful examination of the ground that the differently inclined strata to which he refers are separated by a fault. In other parts of the district, Gunn clearly states that there is no discordance of dip between the various divisions from the base of the Old Red Sandstone to the top of the New Red Sandstone (1903, pp. 25, 28, 67). Hebridean and Antrim experience further shows that the Tertiary volcanic platform never exhibits angular unconformity in regard to the New Red Sandstone or later deposits. Accordingly, it is quite safe to assume that almost all the steep dips characteristic of the Old Red Sandstone, Carboniferous and New Red Sandstone, in the granite region of Arran, are of Tertiary date. Speaking of the arrangement of these three formations in

the vicinity of the northern granite, Gunn remarks " we are driven to the conclusion that the intrusion of the latter has been the principal factor in causing the present arrangement of the strata in question " (1903, p. 132). In this statement, Gunn refers not only to the flexure of the strata, but also to their faulting. It is not safe to claim every important fault of the district as of Tertiary date ; but there is good reason to assent to Gunn's carefully considered opinion " that many, if not most, of the faults are post-Triassic " (1903, p. 161)—an opinion which is developed in his next paragraph to the conclusion quoted above.

3. The greatest thickness of upturned Schists seen on the west side of the North Arran Granite measures 7,000 feet.

The Old Red Sandstone reaches 8,000 feet in thickness south of the granite area ; and much the greater part of this belongs to the Lower division. North of the granite (north-east of Loch Ranza) nothing remains but some 150 feet of the Cornstone Group—nowadays referred to the top of the Upper Old Red Sandstone (Gunn classed it with the Carboniferous). The unconformity of the Cornstones upon the Schists at this locality has been rendered classic by Hutton's description (1899, posthumous, p. 235).

The Carboniferous thins out in exactly the opposite direction. On the north-east coast it measures about 2,500 feet. On the west coast, south of the granite, it is absent altogether.

The New Red Sandstone measures about 3,000 feet.

The Central Arran vent includes foundered masses of Rhaetic, Lias, and Chalk, first interpreted by Peach (1901*a*, p. 226 ; 1903, chap. viii). This demonstrates that in early Tertiary times the New Red Sandstone of Arran had a Mesozoic cover comparable with that of Antrim and Mull. In Antrim, post-Triassic Mesozoic rocks measure less than 400 feet (1904*a*, pp. 24–7). In Mull they range from 0–660 feet (1925*a*, pp. 93, 95, 98, 113).

It is not known whether the Arran Chalk was covered by Tertiary lavas at the time of the granite intrusions. Great thicknesses of such lavas are preserved both in Antrim and Mull.

4. As the absence of angular unconformities shows that the post-Schist sediments of Arran were quite gently inclined until the intrusion of the granites, the details of their updoming are easy to read.

South of the Northern Granite Complex.—The post-Schist sediments are greatly disturbed near the vent of Fig. 2, but apart from this the main features of their attitude is a steep uptilting away from the northern complex.

The Lower Old Red Sandstone generally dips outwards at angles between the vertical and 45°. In Glen Rosa (west of Brodick Bay), it is inverted so as to dip inwards with the same range of inclination.

The Upper Old Red Sandstone almost always has an outward dip, which varies between verticality and 30°.

The Carboniferous always dips outwards, at angles between 75° and 30°.

The lower part of the New Red Sandstone dips outwards, at angles between 60° and 30°.

There are not many transverse faults in this area, and strike faults are not easy to identify. Gunn has given very good reason to suppose that the junction between the Old Red Sandstone and the Schists is a fault (1903, pp. 128, 129). He has also argued that this fault is the pre-Carboniferous Highland Border Fault of Bute, north-east of Arran (presumably, in Arran, distorted by the granite, 1903, p. 131). I do not accept this hypothesis, for it seems to me to suggest that the same Highland Border Fault should cross Kintyre (west of Arran), which is not the case. Moreover, if the arcuate boundary between Old Red Sandstone and Schists owes its shape to lateral displacement due to the introduction of the granite, one would expect folding of the Trias of southern Arran comparable with the folding that borders the Mull plutonic centre (1924*a*, chaps. xii, xiii. Daly has attributed the peripheral folding of south-east Mull to drag communicated downwards from an outwardly slipping cone—1925*b*, p. 296. There is, however, no tendency to outward overturning of the folds). There is, in the ample exposures of South Arran, no peripheral folding attributable to the northern granite. Accordingly, I feel convinced that the fault in question originated as a curved feature with the intrusion of the granite and has only suffered minor bending.

North-east of the Northern Granite Complex.—Great tilting of the post-Schist sediments characterizes this belt; but dips are not as a rule so high as farther south, and for the most part lie between 60° and 20°. A belt of north-westerly faulting plays a very important *rôle* in the structure of the district. North-west, it will be remembered, is the prevalent direction for Tertiary faults and dykes in the Hebrides generally. One rather complex branch of the Arran belt has been traced by Gunn near the north-eastern coast of the island, where, for four miles, it almost completely separates post-Schist sediments from Schists. Another branch forms the approximate border of the granite and has only been very partially realized by Gunn—in fact it has generally been healed up by the consolidation of the granite. The evidence for this inner fault is as follows: In the South (west of Maol Donn), the fault has been followed by Gunn for two miles, almost to Brodick Bay, and has been shown to have an important effect upon the outcrops of various sedimentary groups. Farther north, I have found it, as already stated, breaking down the contact of Old Red Sandstone and Granite exposed in the White Water west of Corrie. The post-consolidation movement along the fault at this point probably accounts for the very restricted alteration of the sandstone to which Tyrrell has drawn attention (1924*b*, p. 408). The alteration only extends for 50 yards from the granite, while elsewhere, in the Schists, it sometimes reaches as much as 300 yards. I do not suggest that the fault even here is really of post-intrusion date, but merely that the upper part of the granite consolidated at a relatively early stage and was locally pushed up along with its roof and thus reopened an old plane of movement. A little north east of the White Water, Gunn has picked up the fault again, where is separates a strip of granite-veined Schist from Old Red Sandstone that strikes obliquely at the line of junction. Beyond this, the fault serves once again as the approximate boundary of the granite, and so far as can be seen is penetrated to some slight extent by the latter. In this part of its course, the existence of the fault is mainly inferred from the fact that the granite margin runs approximately straight, and that the Schists have suffered only to minor degree the distortional uplift characteristically displayed along the remainder of the granite circumference. This brings us to the most interesting feature of our subject.

5. The Schists of Arran consist mainly of grits and phyllites, in the Chlorite Zone of regional metamorphism. On the north-east side of the granite complex, there is found a special series of grits, slates, and pillow-lavas—any one wishing to appreciate Gunn's merits as an observer should verify his observation of chilled edges for the pillows of these lavas in the river bed, North Glen Sannox (1903, p. 20). It is admitted that these lavas and interbedded sediments must be of the same date as the fossiliferous Highland Border Rocks at Aberfoyle and Stonehaven—generally referred to the Upper Cambrian. In Arran, they dip steeply off grits and slates which, from their position with reference to the Loch Ranza Syncline, to be described immediately, clearly lie at the top of the Schist succession as developed on the north-east side of the granite: ' These particular grits, slates, and lavas are cut off to the south-west against the granite, and have not been recognized in any of the exposures to the south or west. Their geographical limitation supplies an additional reason for interpreting the relatively straight north-eastern boundary of the granite as a fault.

In regard to the disposition of the Schists of Arran, Gunn offers the laconic comment, " in the main they have the same north-east and south-west strike as in the Dunoon district [that is, on the mainland farther north-east], but with some variations due apparently to the intrusion of the granite mass in Arran " (1903, p. 12). Fortunately, we can turn from this statement to his one-inch map (1901 and 1910) where the " variations " of strike, that he speaks of so calmly, are portrayed in minute detail, to which Fig. 2 does only partial justice.

North-east of the granite, the dip and strike of the Schists has suffered relatively little disturbance ; and it is here that one can most easily confirm Gunn's interpretation that the normal strike for the district was, in pre-granite times, north-east and south-west, just as it remains to-day in the neighbourhood of Dunoon. He might have added that the normal dip also agrees in direction with the south-easterly dip found at Dunoon, and that in amount it generally exceeds 45°.

In proceeding towards Loch Ranza from the south-east, one finds the strike of the Schists becomes curved. More and more differential movement has occurred within the Schists as a result of the intrusion of the granite. Bending by the granite becomes increasingly prominent in place of block-faulting. The result is a magnificent syncline that crosses Loch Ranza. Its existence can be verified easily on the hill slopes either side of the loch, for instance behind the village near the castle; but the best exposure of the axis of the syncline is by the roadside on the sea-shore west of the loch on the way to Catacol Bay. Here, the south-eastward dipping Schists, that occupy all the north coast of the island farther north-east, flatten out and begin to dip north-west away from the granite. This they continue to do for the whole intervening mile between the axis of the syncline and the margin of the granite. At first, the north-west dip is about 10°, but this mounts gradually until, near the granite, verticality is reached.

I have not been able to find whether Gunn attributed the Loch Ranza Syncline to the granite—as I myself have no hesitation in doing. At any rate, he very clearly realized the existence of the syncline; and it was his description that first led me to it. It reads: "On the eastern side of Catacol Bay there is a marked synclinal fold, which runs nearly parallel to and not far from the coast. The line of it crosses the loch a little north of Loch Ranza Castle, and it can be observed for some distance east of the loch, but gradually disappears, so that from North Newton [north-east of Loch Ranza where cornstones of Old Red Sandstone age, dipping N.W. at 25°, rest on Schists, dipping S.S.E. at 40° (1903, p. 52)] there seems to be a regular and apparently ascending series in the Schists all along the edge of the high ground to the south-eastwards as far as to Corloch, where we come upon the supposed Arenig [or Upper Cambrian] lavas" (1903, p. 15).

The axis of the Loch Ranza Syncline runs parallel to the margin of the granite. Thus, east of the loch, it swings from a west-north-west to a due west course, and, across the loch, goes out to sea near Catacol Bay with a west-south-west trend. A mile or two south-west of Catacol Bay, the main axis probably lies just off the coast, for on land there are two or three minor parallel synclines with south-west strike.

The upward displacement of the Schists exposed in the southern limb of the syncline at Loch Ranza must have attained about 12,000 feet.

The same phenomenon of upheaval is illustrated in the southward deflection of the strike of the Schists along the west side of the granite. There is a fairly good exposure of the Schists along the east coast from Imachar Point southwards. The Schists here are very disturbed, and it has not been possible to determine what share of their disorder they owe to the granite; but it is easy to recognize that they constitute an ascending structural succession towards the south-east. On leaving the coast and proceeding towards the granite, it is also a simple matter to follow the general strike bent to the south-south-east so as to allow of ever lower levels of the Schist succession appearing at the surface as the intrusion is approached. The upturned Schists generally stand almost vertical.

6. I agree with Gunn (or perhaps I go a little farther than he ventured) and claim that the only conceivable cause for the uplift of the Schists and later sediments of North Arran is the intrusion of the granite complex. This uplift must have been accompanied by a slight outward movement—as indeed is shown by definite reversal of Old Red Sandstone in Glen Rosa west of Brodick Bay.

The Vredefort Mountain Land.

1. There is a central granite, which, with very subordinate Schists, occupies a circular outcrop 40 km. (25 miles) wide. This Vredefort Granite is regarded as older than the surrounding sediments, largely because it does not vein them. Moreover, the granite itself is abundantly veined by pegmatites that do not stray into the adjacent sediments. "Where the contact could be studied —as a rule it is covered by surface soil—it always gives the impression as if the sediments of the Witwatersrand have been deposited on a much older granite-soil" (1925, p. 21). Readers might hope for a more positive statement in this last respect, but they must realize that the rocks bordering the granite are highly metamorphosed, so that it is difficult to determine their original characters. Perhaps the most compelling reason for accepting the authors' interpretation of the age of the granite relative to its envelope is the fact that from 1901–1904 Molengraaff himself thought the granite intrusive (1925, p. 5). On the other hand, even to-day, the authors admit that the Vredefort Granite is in some important respects unlike other "older granites" (pre-Witwatersrand) of the Southern Transvaal (1925, pp. 15, 22); and they state that "it is quite conceivable that during its peculiar tectonic history it may have undergone metamorphism connected with the younger magma [to which further reference will be made in the sequel] and have been altered ('contaminated') by some elements derived from it". (1925, p. 169.) For the purposes of the present paper, it is assumed that the Vredefort Granite is essentially pre-Witwatersrand.

2. A succession of sediments some 13,000 m. (43,000 feet) thick surrounds the granite. There seems no doubt that these sediments have been correctly correlated with their equivalents elsewhere, and that their oldest members lie nearest the granite. In spite of this, there is a very general inward dip towards the granite. "These sediments are tilted and for the greater part overtilted, and

hence dip in many places radially into the granite. The consequent inversion of the succession affects in places not less than 1,000 m. of sediments from the granite periphery outwards" (1925, p. 174).

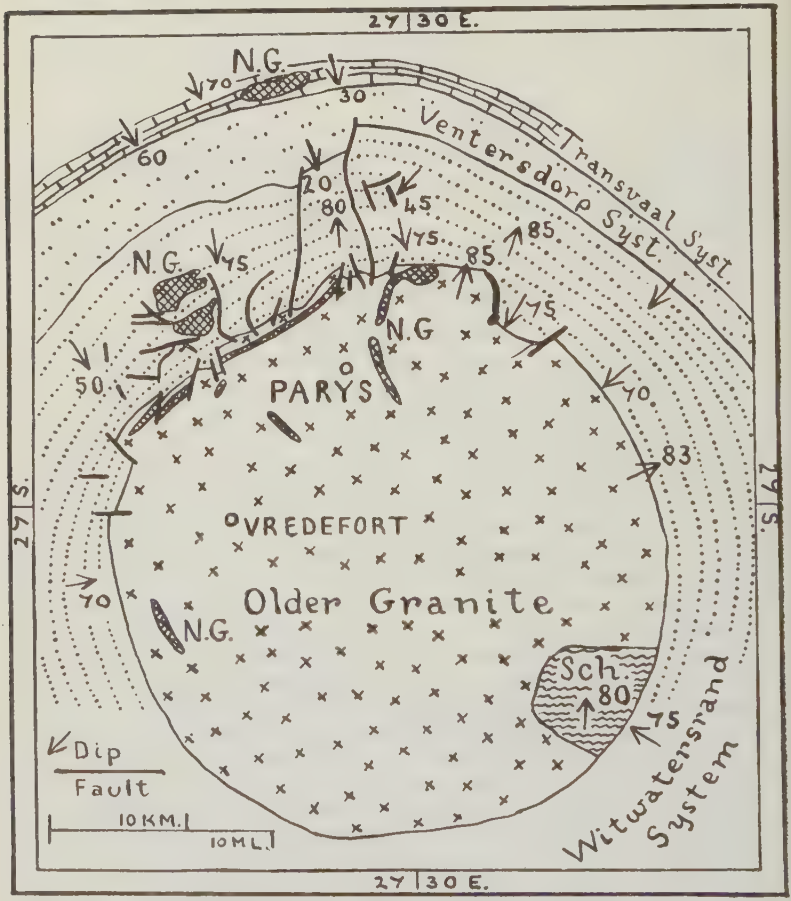

FIG. 3.—Map of Vredefort Dome. Sediments, with Witwatersrand System at their base, upheaved and inverted around Older Granite and Schists. N.G. = Newer Granite and Gabbro. Outcrops of unconformable Karoo System omitted. After A. L. Hall and G. A. F. Molengraaff's coloured plate, 1925. These authors acknowledge indebtedness to E. T. Mellor, F. W. Penny, and L. T. Nel.

3. There is much metamorphism of the sedimentary pile and of its associated lavas. Thus we note "the occurrence all round the granite of the very common garnet-amphibole-hornfels derived from the ferruginous Water Tower Slates and the conversion of

the lavas of the Basal Amygdaloid into hornblende-granulite" (1925, p. 134). This particular all-embracing metamorphism is of quite moderate extent measured outward from the Vredefort Granite, and has been ascribed by the authors to pressure metamorphism (connected either with weight of cover or with pressure of upheaval) acting at a depth-temperature of 400° C. (1925, p. 176). They admit, however, that Rogers has found no similar metamorphism in the Heidelberg area where, apart from doming, the conditions seem similar (1925, p. 136). This leads them to suppose that the pressures developed in the act of doming may have had an important share in determining the mineral development at Vredefort. I venture to suggest that a temperature of considerably over 400° C. was an essential factor in the operation, and that heat was being transferred through the Vredefort Granite from a subterranean intrusion that determined the dome. At any rate, as we shall see in the next paragraph, there seems no escape from the hypothesis of a subterranean intrusion with approximately the required position.

4. In the north-west sector of the tilted zone, the metamorphic affects spread out from the Vredefort Granite for as much as 6·5 km. In this widely extended belt, pelitic sediments are very often in the condition of andalusite-cordierite-biotite-hornfels. The authors adopt the view that the metamorphism of this part of the area was caused by "the emplacement of a large younger intrusion, to a great extent concealed though exposed as three small bosses of alkali granite, basic marginal intrusions in the granite, etc." (1925, p. 176; see also N.G. Fig. 3 of present paper).

5. It is fairly clear that the "younger intrusion" of the previous paragraph must lie with an approximately flat upper surface below the tilted sediments which it metamorphoses over so extensive an area. I do not propose to consider it as a cause of the tilting, but rather as a comparatively late offshoot from the magma that previously had developed the dome. Hall and Molengraaff clearly recognize a geographical connexion between their "younger intrusion" and the dome. They speak of localization of the younger intrusion by domal stress (1925, p. 177).

6. It will be gathered from the last three paragraphs that Hall and Molengraaff distinguish very definitely between the modes of origin of the metamorphism that surrounds the Vredefort Granite and that which extends north-westwards from its margin. They cannot, however, link up their hypothesis with any specific differences of mineral development in the two cases. In a broad sense, differences have been noted, but these differences are correlated with differences of original composition (1925, p. 124). Thus garnet-amphibole-hornfels and hornblende-granulite represent the ferruginous Water Tower Slates and the Basal Amygdaloid *all round* the Vredefort Granite, and their only special characteristic in the north-west sector seems to have been a "reinforcement of

crystallization "—" the metamorphosed Water Tower Slates are in this district often very coarse and extremely rich in garnet, while the hornblende-granulite of the Basal Amygdaloid, is also distinctly coarser " than elsewhere (1925, p. 142). Moreover, in this same north-west sector, where the garnet-amphibole-hornfels comes in contact with andalusite-cordierite-biotite-hornfels, we read that the difference of mineral content is dependent upon difference of original composition. " On top of these, somewhat less ferruginous beds follow, in which are intercalated non-ferruginous rocks, originally clay-shales or slates now altered into cordierite-biotite-hornfels and andalusite-cordierite-biotite-hornfels generally well stratified " (1925, p. 28). From these citations, it appears that Hall and Molengraaff's separation between a surrounding *pressure-metamorphism* and a north-west *temperature-metamorphism* is distinctly speculative. It seems easier to me to interpret both metamorphisms as essentially thermal: to attribute the circumferential metamorphism to a centrally placed intrusion which domed the Vredefort Granite and superincumbent sediments; and to interpret the north-westwardly extended metamorphism as due to a comparatively late north-west extension of the central intrusion beneath the tilted sediments.

7. Hall and Molengraaff's explanation of the updoming is that it " was initiated by centripetal pressure. The relief of load resulting from this movement caused a younger magma below the granite to become active and to rise and thus to assist the updoming and the upward movement of the much heated but passive granite " (1925, p. 177). In other words: " The present structure of the Vredefort Mountain Land is based on centripetal pressure as the major cause associated with a ' point ' uplift as a minor cause and dependent upon the emplacement of a younger magma " (1925, p. 162). My own suggestion is that *there has been no centripetal pressure, but merely central upheaval, accompanied by its necessary correlative, centrifugal pressure*; and I accept the younger magma of the authors as the cause of the upheaval.

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The Zonal Distribution of the Larger Foraminifera of the Eocene of Western India.

By W. L F. Nuttall, D.F.C., Ph.D., F.G.S., The Sedgwick Museum, Cambridge.

INTRODUCTION.

AN extensive collection of Eocene Foraminifera was made during a geological reconnaissance of parts of Western India undertaken on behalf of the Whitehall Petroleum Corporation by Mr. D. Dale Condit and myself. Further specimens have been lent by the Indian Geological Survey. As traced from north to south the region examined includes parts of the Dera Ghazi Khan District in the Punjab; the Loralai District, the Bugti Hills, the Bolan Pass, Kalat and Las Bela States in Baluchistan; the Laki Range and Indus valley in Lower Sind; and Cutch State. The distance from the northernmost area examined to the southernmost is approximately 550 miles. I have already published a brief account of the stratigraphical geology with palaeontological descriptions of the species of Foraminifera encountered (3 to 8).[1] In this paper it is proposed to summarize the results of this investigation and compare briefly the zonal distribution and evolution of the species with that of the European Eocene.

In the palaeontological details already published a list of occurrences of each species is given, and the annexed table (No. II) shows the stratigraphical distribution of the larger Foraminifera based solely on these records. With increased knowledge it is not improbable that the less common species may be found to have a wider vertical range than indicated in the table.

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[1] Numbers in parentheses relate to references at the end of the paper.

THE GEOLOGICAL SUCCESSION.

In descending sequence the geological succession is as follows:—

TABLE I.

Name of Formation.	*Approximate thickness in feet.*	*Age referred to the classification of the European Tertiary.*
(1) Lower and Middle Kirthar Series.	attains a maximum of 4000	Middle Eocene (equivalent to the Lutetian).
(2) Laki Series . .	500 to 1600	Lower Eocene (approximately equivalent to part of the Thanetian and Ypresian).
(3) Upper Ranikot Series.	800	Basal part of the Lower Eocene (possibly equivalent to the Montian and part of the Thanetian, *sensu lato*).

These formations are of marine origin. The Upper Ranikot Series, which is only found in Lower Sind, consists of alternations of limestone and shale. Occasional sandy beds are intercalated, which indicate that when these strata were being laid down a land surface existed at no great distance.

In Lower Sind the Laki Series is composed mostly of limestone, whereas in parts of Baluchistan further north shale predominates, the foraminiferal faunas of the two areas being, however, very similar. In the Laki Series of Lower Sind two lateritic horizons occur, which represent local unconformities, when for short periods terrestrial conditions prevailed. The interbedded marine limestones are, however, white and of purely organic origin with no mineral detrital matter, showing that they were deposited in clear water.

The lithology of the Lower and Middle Kirthar Series is very constant, these beds consisting of alternations of creamy white nummulitic limestone and fine gray shale. As stated elsewhere I have not examined the Upper Kirthar Series. In the area under discussion the Lower and Middle Kirthar Series is devoid of coarse sediments, indicating that these beds were deposited in a tranquil sea of moderate depth. It is evident that during the formation of the Eocene strata in Western India the conditions of deposition varied little. This is important as it precludes the possibility of the variations in fauna depending on variations in facies. It is clear from an examination of Table II that the stratigraphical divisions given can be easily recognized by their distinctive faunas of Foraminifera. The very marked difference between the fauna of the Upper Ranikot and that of the Laki Series is partly explained by there being an unconformity between the two formations. Similarly there is probably a stratigraphical break between the upper and lower divisions of the Middle Kirthar.

THE ZONE FOSSILS.

The larger Foraminifera, which include in particular the Nummulites, Assilines and Orbitoides, possess a complicated internal structure subject to rapid evolutionary changes; and since these fossils occur in large numbers they are valuable as time-indices. Of the well-known workers on the group Hantken, de la Harpe, Boussac, and Professor H. Douvillé have shown that in Europe *Nummulites* and *Assilina* may be used as zone fossils. It is recognized that in the former genus the morphological feature of particular significance is the development of the septal filaments in the outer skeleton of the test. The Orbitoides are also of stratigraphical value as has been proved by the researches of Professor H. Douvillé, Dr. A. Silvestri, Dr. T. W. Vaughan, and several others. Table III gives a list of the species of the larger Foraminifera common to Western India and the Eastern Hemisphere. The horizons of which they are characteristic are indicated, the identifications and stratigraphical horizons of some of the extra-Indian species having been discussed at greater length elsewhere (3 to 8).

Nummulites.

Of the sixteen species of Nummulites[1] that have been described from Western India, ten have been recorded from strata of known age in Europe. It will be observed by an examination of Table III that the stratigraphical range of the European species is approximately the same in the two regions.

Table IV shows the horizons, classification, and some suggested lineages of the Nummulites in Western India. The Upper Ranikot is the lowest horizon from which Nummulites have been recorded, and the two species that occur (*N. planulatus* and *N.* aff. *guettardi*) are devoid of pillars in the septal filaments. In the Laki Series the Nummulites are also only of this type, and include *N. mamilla* ?, *N. irregularis*, and *N. atacicus*. Of the above species *N. guettardi* and *N. mamilla* are closely related. They are small megalospheric radiate forms commonly with a bicellular nucleoconch. *N. atacicus*, which is very common in India, ranges up into the lower part of the Middle Kirthar. Of the radiate Nummulites found in the lower part of the Middle Kirthar *N. beaumonti* and *N. stamineus* are probably descended from the *N. atacicus* stock. The former has been regarded by some authors as a variety of *N. atacicus*. The latter is a new species, the European form it resembles most being *N. discorbinus*. In the upper part of the Middle Kirthar radiate Nummulites are rare, the group being represented by small forms, which are very difficult to determine and have been given no specific names.

In the Lower Kirthar Nummulites with pillars in the septal

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[1] Each of these species may include two forms, the microspheric and megalospheric, both of which have been assigned distinct specific names.

TABLE II.—TABLE SHOWING THE STRATIGRAPHICAL DISTRIBUTION OF THE LARGER FORAMINIFERA OF THE LOWER AND MIDDLE EOCENE OF PARTS OF WESTERN INDIA.

Genus and Species.	UPPER RANIKOT SERIES.	LAKI SERIES.			KIRTHAR SERIES.		
		Meting and Dunghan Limestones.	*Laki Limestone.*	*Ghazij Shales.*	*Lower Kirthar.*	*Lower part of Middle Kirthar (B).*	*Upper part of Middle Kirthar (A).*
**Nummulites planulatus* Lamarck	— *f* —	....	....	....	....	....	....
†*Nummulites* aff. *guettardi* d'Archiac	— *c* —	....	....	....	....	....	....
†*Siderolites miscella* d'Archiac & Haime	— *f* —	....	....	....	....	....	....
**Assilina ranikoti* Nuttall	— *a* —	....	....	....	....	....	....
**Operculina canalifera* d'Archiac	— *f* —	....	....	....	....	....	....
Operculina hardiei d'Archaic & Haime	— *c* —	....	....	....	....	....	....
**Dictyoconoides conditi* Nuttall	— *r* —	....	....	....	....	....	....
†*Alveolina oblonga* d'Orbigny	........—	— *c* —	— *c* —	....	....	....	....
†*Flosculina globosa* (Leymerie)	........—	— *va* —	....	....	....	....	....
**Alveolina lepidula* Schwager	....	— *r* —	....	....	....	....	....
Opertorbitolites douvillei Nuttall	....	— *r* —	....	....	....	....	....
†*Alveolina subpyrenaica* Leymerie	....	— *va* —	— *va* —	....	....	....	....
†*Nummulites* (?) *mamilla* Fichtel & Moll.	....	— *f* —	— *f* —	....	....	....	....
**Nummulites irregularis* Deshayes	....	— *r* —	....	— *f* —	....	....	....
Assilina granulosa d'Archiac (& *leymeriei* d'Archiac).	....	— *a* —	— *a* —	— *va* —	....	....	....
†*Alveolina ovicula* Nuttall	....	....	....	— *r* —	....	....	....
†*Discocyclina archiaci* Schlumberger var. *baluchistanensis* Nuttall.	....	....	....	— *r* —	....	....	....
Nummulites atacicus Leymerie (& *subatacicus* Douvillé).	....	— *a* —	— *f* —	— *a* —	— *a* —	— *a* —	....
Orbitolites complanata Lamarck	....	— *a* —	— *c* —	———	———	———	— *r* —
Assilina exponens (Sowerby) (& *mamillata* d'Archiac).	....	....	....	......—	— *c* —	— *a* —	....
Nummulites obtusus Sowerby (& *perforatus* (de Montfort)).	....	....	....	....	— *r* —	— *a* —	— *c* —

Genus and Species.	UPPER RANIKOT SERIES.	LAKI SERIES.			KIRTHAR SERIES.		
		Meting and Dunghan Limestones.	*Laki Limestone.*	*Ghazij Shales.*	*Lower Kirthar.*	*Lower part of Middle Kirthar (B).*	*Upper part of Middle Kirthar (A).*
Nummulites acutus Sowerby (& *djokdjokartae* Martin).						*f*	
**Nummulites beaumonti* d'Archiac & Haime						*f*	
**Nummulites maculatus* Nuttall						*r*	
**Nummulites stamineus* Nuttall						*f*	
**Dictyoconoides cooki* (Carter)						*a*	
†*Actinocyclina alticostata* Nuttall						*r*	
**Discocyclina dispansa* (Sowerby)						*a*	
**Discocyclina javana* (Verbeek) var. *indica* Nuttall						*va*	
†*Discocyclina undulata* Nuttall						*r*	
**Discocyclina sowerbyi* Nuttall						*c*	*r*
†*Alveolina elliptica* (Sowerby)						*c*	*r*
Nummulites laevigatus (Bruguière) (& *lamarcki* d'Archiac).						*r*	*a*
**Nummulites* aff. *scaber* Lamarck							*a*
**Nummulites carteri* d'Archiac & Haime							*r*
**Nummulites gizehensis* (Forksal)							*r*
Assilina cancellata Nuttall (& *subcancellata* Nuttall).							*f*
Assilina papillata Nuttall (& *subpapillata* Nuttall).							*c*
**Assilina spira* de Roissy							*f*

* = microspheric. † = megalospheric. *r* = rare. *f* = frequent. *c* = common. *a* = abundant. *va* = very abundant.
Megalospheric forms of *Nummulites* and *Assilina* are placed in brackets after the microspheric forms of the same species.

TABLE III.—TABLE SHOWING THE SPECIES OF LARGER FORAMINIFERA COMMON TO WESTERN INDIA AND OTHER PARTS OF THE EASTERN HEMISPHERE WITH HORIZONS AT WHICH THEY CHARACTERISTICALLY OCCUR.

Genus and Species.	*Horizons in India.*			*Horizons in Europe and elsewhere.*		
	Upper Ranikot. Lower Eocene.	*Laki Series. Lower Eocene.*	*Lower and Middle Kirthar Series. Middle Eocene.*	*Thanetian to Ypresian.*	*Lutetian.*	*Auversian (Ledian) to Bartonian.*
Nummulites acutus Sowerby	—	—	×	—	Java.	—
,, *atacicus* Leymerie	—	×	×	Europe.	Europe, etc.	—
,, *beaumonti* d'Archiac & Haime	—	—	×	—	Egypt.	—
,, *carteri* d'Archiac & Haime	—	—	×	—	Madagascar.	—
,, *gizehensis* (Forksal)	—	—	×	—	Europe, etc.	—
,, *guettardi* d'Archiac, Douvillé	× (aff. *guettardi*)	—	—	Southern France.	—	—
,, *irregularis* Deshayes	—	×	—	Europe.	Europe, etc.	—
,, *laevigatus* (Bruguière)	—	—	×	—	Europe, etc.	—
,, *mamilla* Fichtel & Moll, Douvillé	—	× (? *mamilla*)	—	Southern France.	—	—
,, *obtusus* Sowerby	—	—	×	—	Europe, etc.	Europe.
,, *planulatus* [1] Lamarck	×	—	—	Europe, etc.	—	—
,, *scaber* Lamarck	—	—	× (aff. *scaber*)	—	Europe.	—
Assilina exponens (Sowerby)	—	—	×	—	Europe, etc.	Europe.
,, *granulosa* d'Archiac, Douvillé	—	×	—	Southern France.	—	—
,, *spira* de Roissy	—	—	×	—	Europe.	—
Flosculina globosa Leymerie, Nuttall	×	×	—	Europe.	Italy.	—
Alveolina elliptica (Sowerby)	—	—	×	—	Madagascar.	—
,, *lepidula* Schwager	—	×	—	Egypt.	—	—
,, *oblonga* d'Orbigny	×	×	—	Europe.	Europe.	—
,, *subpyrenaica* Leymerie, Nuttall	—	×	—	Europe.	Italy.	—
Orbitolites complanata Lamarck	—	×	×	Europe, etc.	Europe, etc.	Europe, etc.

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[1] I have pointed out elsewhere (6) that the forms from India assigned to this species have certain distinctive characters not found in typical European representatives.

filaments appear, being represented at first by *N. obtusus* (= *perforatus* = *aturicus*, auctorum). Radiate and pilate Nummulites range throughout the Kirthar Series. Of the pilate Nummulites with meandriform septal filaments *N. maculatus*, *N. carteri*, and *N. gizehensis* show characters in common, and are doubtless related to one another. The pilate Nummulites with reticulate filaments of simple mesh include *N. obtusus*, *N. laevigatus*, *N. acutus*, and *N.* aff. *scaber*. Of these *N. acutus* (= *vredenburgi*) and *N.* aff. *scaber* are allied to *N. laevigatus*.

The completely reticulate Nummulites are found only in beds of Oligocene age, *N. intermedius* being a species also occurring in Europe, where its stratigraphical range is from the Chattian to Lattorfian. They are commonly associated with *Lepidocyclina* (*Eulepidina*) *dilatata* (Michelotti).

Assilina.

Six microspheric forms of the genus *Assilina* are recorded from Western India, three of which occur in Europe (see Table III). Four of the Indian species (*A. ranikoti*, *A. granulosa*, *A. exponens*, and *A. cancellata*) are clearly related, and forms intermediate between normal types of each of the species are occasionally found. They are believed to constitute a lineage showing marked evolutionary development. There are four morphological characters which undergo a continuously progressive change, the stages reached by typical representatives of each species being shown in Table V. The earliest form, *A. ranikoti*, is of small size, externally very granular, and internally with curved septa in the median layer, while the latest form, *A. cancellata*, is large, smooth, and possesses straight septa. It is also significant that the diameter of the test of *A. exponens* is greater in specimens from the Middle Kirthar than in forms found at lower horizons.

The Assilines appear to have reached their maximum development as regards size and number of species in the upper part of the Middle Kirthar, and it is from this level that I have described *A. cancellata*, which is the largest recorded species of the genus. Except for *A. ranikoti* the associated megalospheric forms of the other three species have been found and in each case exhibit the principal characters of their respective microspheric forms. Two other Assilines, *A. papillata* and *A. spira*, occur in the upper part of the Middle Kirthar, and are both probably allied to *A. exponens*.

Of the above species *A. granulosa* and *A. exponens* occur in Europe, where they are sometimes difficult to distinguish from one another. In consequence confusion exists in Europe as to the stratigraphical horizons at which the two species are found. Professor H. Douvillé (2) has shown that in Southern France *A. granulosa* is restricted to the Lower Eocene and *A. exponens* is characteristic of the Middle Eocene. This agrees with the distribution observed in India.

TABLE IV.—TABLE SHOWING HORIZONS, CLASSIFICATION AND SUGGESTED LINEAGES OF NUMMULITES OF WESTERN INDIA.

Stratigraphical Horizon.	*Nummulites without Pillars in the Septal Filaments.*		*Nummulites with Pillars in the Septal Filaments.*		
	Septal Filaments. radiate.	*Septal Filaments meandriform.*	*Septal Filaments meandriform.*	*Septal Filaments reticulate.*	
				Simple mesh.	*With transverse Laminae.*
NARI SERIES. (Oligocene, Stampian.)	—	—	—	—	*intermedius.* *clipeus.*
UPPER PART OF MIDDLE KIRTHAR. (Middle Eocene.)	Small indeterminate species, rare.	—	*gizehensis* *carteri*	aff. *scaber*	—
LOWER PART OF MIDDLE KIRTHAR. (Middle Eocene.)	*stamineus* *beaumonti*	—	*maculatus*	*acutus* *laevigatus*	—
LOWER KIRTHAR. (Middle Eocene.)		—	—	*obtusus*	
LAKI SERIES. (Lower Eocene.)	*mamilla* ? *atacicus*	*irregularis*	—	—	—
UPPER RANIKOT. (Lower Eocene.)	aff. *guettardi*	*planulatus*	—	—	—

TABLE V.—TABLE SHOWING EVOLUTION IN THE GENUS ASSILINA.

Genus and Species.	*Average diameter in mm.*	*Average number of whorls.*	*External Ornamentation.*	*Shape of septa of median layer.*	*Stratigraphical horizon in India.*
Assilina cancellata Nuttall . .	35	25	Smooth.	Straight.	Upper part of Middle Kirthar.
,, *exponens* (Sowerby) . .	15 to 20	10	Granular to smooth.	Straight.	Upper part of Laki Series to upper part of Middle Kirthar.
,, *granulosa* (d'Archiac) . .	7	8	Granular to smooth.	Curved near outer	Laki Series.

Orbitoides.

Orbitoides of the genus *Discocyclina* are found throughout the Eocene strata of Western India, and the species appear to be all somewhat different from those from Europe or other parts of the Orient. The species of *Discocyclina* in the Upper Ranikot and Laki Series are small and thin; the pillars of the lateral layer being small and of equal size. The genus is abundant in the lower part of the Middle Kirthar, where there are four species all possessing large pillars in the lateral layer. Of these *D. dispansa* and *D. javana* var. *indica* resemble forms from the East Indies. In addition one species of *Actinocyclina* has been recorded. The genus *Lepidocyclina* appears in the Oligocene Nari strata (8, 9).

Alveolina.

The Alveolines are represented by six species, of which five are found only in the Laki Series. In this formation thick limestone beds occur almost entirely made up of *Alveolina subpyrenaica*, *A. oblonga*, and *Flosculina globosa*. The other species from this horizon are *A. lepidula* and *A. ovicula*. *A. elliptica*, which is found in the Kirthar Series, may be readily distinguished from the Laki forms by its larger diameter. Five of the above species are found outside India at horizons given in Table III.

Other Genera.

The other larger Foraminifera include the following:—(1) One species of *Siderolites*[1] found in the Upper Ranikot. As stated elsewhere the form it resembles most is *S. vidali* of the European Upper Cretaceous. (2) Two species of *Operculina*[1] from the Upper Ranikot. (3) One species of the genus *Opertorbitolites*, allied to *Orbitolites*, from the Laki Series. (4) *Orbitolites complanata* which ranges throughout the Laki and Kirthar Series. (5) Two species of the peculiar genus *Dictyoconoides*, which has so far been recorded only from India. One is a small form (*D. conditi*) found in the Upper Ranikot and the other (*D. cooki*) is larger and more complex; it is common in the lower part of the Middle Kirthar. Major L. M. Davies (1) has recently published a description of three other species of this genus. They were collected from beds which he classifies as Eocene from North-West India.

THE USE OF THE FORAMINIFERA TO THE FIELD GEOLOGIST.

If both microspheric and megalospheric forms are regarded as distinct species I have recognized forty-seven species of larger Foraminifera in the Eocene of Western India. It is evident that the field geologist is not in a position to distinguish a large number of these, particularly as some of the Nummulites can only be identified with certainty by preparing thin sections. The following forms are, however, easy to recognize by their external appearance, and are accordingly of practical use in the field :—

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[1] Dr. T. W. Vaughan has recently sent me some Foraminifera collected from the Kirthar Series (Middle Eocene) of Ghalha, about 150 miles north of Bombay. Among other forms these include one species each of *Operculina* and *Siderolites*. The species differ from those I have recorded from the Lower Eocene of Sind.

Upper Ranikot.	Only radiate *Nummulites*. *Operculina* common. *Siderolites*. Small very granular *Assilina*. Small thin *Discocyclina*.
Laki Series.	Abundant *Alveolina*. *Orbitolites* common. Only radiate *Nummulites*. Thin granular to smooth *Assilina*. Small thin *Discocyclina*.
Lower Kirthar.	Appearance of pilate *Nummulites*. Medium sized *Assilina*.
Middle Kirthar, Lower part (B).	Large *Discocyclina* common. Pilate and radiate *Nummulites*. Large *Alveolina*. Large *Dictyoconoides*.
Middle Kirthar, Upper part (A).	Large *Assilina*. Pilate and occasional small radiate *Nummulites*.

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(6) —— " The Larger Foraminifera of the Upper Ranikot Series (Lower Eocene) of Western India " : Geol. Mag., Vol. LXIII, 1926, pp. 112–21, 2 pls., 3 text-figs.

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Petrological Notes on the Old Red Sandstone of the West Midlands.

By W. F. Fleet, M.Sc., A.I.C., F.G.S.

(PLATE XXIX.)

Introductory.

THE chief purpose of the present communication is to draw attention to results accruing from the use of improved methods in heavy mineral investigation. In an earlier paper by the present author (1),[1] a summarized description was given of the chief minerals observed in certain Devonian rocks occurring in Shropshire and other localities in the West Midlands. Mention was made of the extreme abundance of garnet in the Downtonian and Dittonian rocks, while an increase in certain other minerals in the Upper Old Red (Farlow) Sandstone was indicated. At that time the relative proportions of the various minerals were arrived at largely by eye-estimation, with the result that no great distinction was drawn between the quantity of garnet present in the Downtonian and that in Dittonian rocks. Reference, however, to the tables of frequency given in the paper shows that the mineral in question was regarded as being normally present in extreme abundance in the Downtonian beds, while in the Dittonian beds it was tabulated as " abundant " or " very abundant ", only one case of extreme abundance being given. Recently, the author has adopted methods involving accurate counting of large numbers of the mineral grains, together with representation of relative frequency of occurrence by actual percentages. The results following the application of this improved procedure to the Old Red Sandstone residues are so marked in character that it seems desirable to put forward the following notes as an illustration of the additional and more accurate data obtainable thereby.

Estimation and Representation of Mineral Composition.

It has been found that certain difficulties arise if mental estimations of relative proportions are made, unsupported by actual counting of the grains. A general inspection of a slide of heavy minerals, checked by counting the grains in, say, half-a-dozen microscope fields, may give an idea of the relative proportions in which the various detrital minerals occur, but has often been found inaccurate and misleading. Further, and short of actual counting of the grains, it is difficult to decide by eye-estimation alone, which of two adjacent figures of a numerical scale, showing more than five degrees of frequency, should be used. In the latter case an alternative would be to return to the simpler representations that have been employed from time to time, whereby three or five symbolical signs are used.[1]

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[1] Figures in parentheses refer to the list of works given at the end of this communication.

Such might be sufficient in cases where wide variation in mineral composition exists, but to obtain accurate results that may readily be compared with those of other workers actual counting of the grains is considered essential. The counting of large numbers of grains may seem, at first sight, a tedious task, but it has been found that, using, say a $\frac{4}{10}$in. objective with an eye-piece giving a large field, and by employing a mechanical stage, it is not a difficult matter to traverse the whole width of a slide several times, counting every grain. According to the closeness with which the minerals appear on the mount it may be necessary to count the grains in anything from twelve to fifty fields, and the number of grains may range from 500 to 1,000 or even more. Reliable figures are then available concerning the true relative frequency of occurrence of the various minerals present on the slide, especially if the grains have been evenly distributed and mixed when mounting the residue, and the accuracy of such figures has been proved repeatedly by counting the grains on different parts of the same slide. Considering next the method of representation of the percentages so obtained, it may be stated that the author formerly indicated (4) the relative frequency of occurrence of the various detrital minerals present in a given residue by means of symbols, one to five in number, according as a mineral was rare or abundant. Later it was considered that this representation was not sufficiently detailed, and a method similar to that employed by other workers in sedimentary petrography was adopted in the paper on the Midland sediments (1), numbers one to ten being used to indicate degrees of frequency from " very scarce " to " extremely abundant ". It has always been felt, however, that there were certain objections to both these methods of indicating the frequency of the different minerals. The former gives no indication of relatively small variations which have been found to be of considerable value in the case of Midland sediments, while the latter is open to objection on several grounds. In addition to the difficulty in deciding, by eye-estimation alone, between adjacent figures in the scale, it is apparent that different workers may hold widely divergent opinions concerning the meanings of the terms " occasional ", " very frequent," " abundant," etc. Again, although it is understood that the numbers are not *really* relative, i.e., they are merely used as convenient symbols for certain accepted terms, there may be a tendency for them to be regarded as actually indicating relative amounts. For example, zircon and tourmaline occur in the Midland sediments in amounts of the order of 20 per cent or 30 per cent and 1 per cent respectively, and it is plain that the representations of these frequencies by eight or nine (abundant or very abundant) and two or three (scarce or occasional) may unintentionally convey a false

[1] See papers by Burton (2), and Neaverson (3), etc.

impression as to the *relative amounts* of the two minerals in a given residue. It is therefore considered advisable to express mineral proportions as actual percentages. Objection may be raised to this on the ground that percentage figures are not simple to read at a glance, but in the case of regular workers in this field of research it will be found that, having once become accustomed to representation by percentages, the significance of such figures can be instantly grasped when comparing results with those of other investigators, and since the percentage figures are exact representations of mineral frequency, the personal element is eliminated when such comparisons are instituted. In the case of geological workers less acquainted with heavy mineral investigation, it seems more convenient for such to be presented with a straightforward percentage table, than one in which some other method of representation has to be understood as a preliminary. It is of course possible, by plotting certain agreed percentages against the units of an arbitrary scale of numbers such as one to ten, to utilize that scale as a means of representation, but such appears quite unnecessary.

THE OLD RED SANDSTONE OF THE WEST MIDLANDS.

The further investigation of the Devonian rocks by the author is the result of a suggestion by Mr. Wickham King, to whom the author is indebted not only for a large number of excellent and typical samples covering an extensive vertical range, but for many useful suggestions. It is hoped that the petrological information here put forward may prove of assistance to him and other workers with regard to the true interpretation of the conditions of deposition between Silurian and Carboniferous times.

The nomenclature of the strata is based on a recent contribution by Mr. King, relating to the Old Red Sandstone of Shropshire (5). The Brownstones, poorly represented in that area, have not been examined. From a large number of samples, the following were selected for investigation, their heavy residues being obtained and examined microscopically. Samples marked with an asterisk were provided by Mr. King, and heights above the Ludlow Bone-bed are fixed by him.

FARLOW SANDSTONE.

1. Gritty, yellow, friable sandstone, with occasional vein-quartz pebbles, from Prescott, S.S.E. of Stottesdon, from about the same zone as Nos. 6–7.

2*. Hard, green, and fawn-coloured micaceous, and fine-grained sandstone, from the south side of Clee Burf, Brown Clee Hill.

3*. Pale green, hard, fine-grained sandstone, from Farlow Bank, Titterstone Clee, from near No. 5.

4. From the prominent quartz conglomerate near the top of Farlow Bank, about 90 yards north of Farlow Vicarage. Yellowish-

white, coarse, friable sandstone, with abundant pink and white vein-quartz pebbles.

5. Greenish dark-banded, hard, medium-grained, and faintly calcareous sandstone from below the conglomerate, and about 25 yards farther to the north-west.

6. Yellowish-green, hard, fine-grained sandstone below No. 5, and about 20 yards north-west of that sample, on the north-west side of a steep way or gully.

7. Yellow to greenish, red-banded, coarse and gravelly, friable sandstone a little below No. 6, exposed on the south-west side of the road at Farlow Bank.

No. 4 is from close below the base of the Avonian; Nos. 5, 6, and 7 are successively lower, and No. 2 is the lowest.

DITTONIAN.

8 and 8*a*. Two samples of hard, purplish, and green, calcareous, and micaceous sandstone, with marly pellets, from Hopton Wafers (probably about 2,600 feet above L.B.B.).

9. Yellowish-green, clayey, micaceous, friable sandstone, from roadside one mile west of Cleobury Mortimer Church (2,700 feet or more above L.B.B.).

10*. Greenish-purple, fine-grained, hard, calcareous sandstone with marl pellets, from Hall Barn Quarry, Trimpley: *Hall Barn Cornstones* of King (2,500 feet above L.B.B.).

11*. Glaucous-green to purple, micaceous, fine-grained sandstone, hard and calcareous, with Pteraspis fragments, from Trimpley: *Guildings Brook Fish Zone* of King (2,250 feet above L.B.B.).

12*. Hard, purple, fine-grained, micaceous, and calcareous sandstone from Birch Hill, Shatterford: *Cephalaspis Sandstone* of King (2,100–2,130 feet above L.B.B.).

DOWNTONIAN.

13*. Coarse, greenish, hard, micaceous, and faintly calcareous sandstone from Birch Hill, Shatterford: *Eurypterid Grits* of King (1,930 feet above L.B.B.).

14*. Greenish-purple, "nodular," calcareous rock with yellow and purple pellets, from Birch Hill, Shatterford: *Psammosteus Limestone* of King (1,850 feet above L.B.B.).

15*. Hard, purplish, fine-grained, micaceous sandstone from Wordley Brook, Netherton Farm, Abberley: upper part of *Ischnacanthus Zone* of King (1,500 feet above L.B.B.).

16*. Greenish-purple, "nodular" sandstone or cornstone. Very micaceous, calcareous and hard, with fish-remains, from Man Brook, Trimpley: lower part of *Ischnacanthus Zone* of King (1,440 feet above L.B.B.).

17*. Gritty sandstone, greenish-grey to fawn in colour, hard but not calcareous, 2 miles south-west of Holdgate, in Corve Dale: *Holdgate Sandstone* of King (920 feet above L.B.B.).

18. Purplish-green, micaceous, hard, fine-grained sandstone, 1½ miles south-south-east of Ledbury Church on Bromsberrow road (within 600 feet of L.B.B.).

19*. Purplish-green, medium to coarse-grained, micaceous and calcareous sandstone, with fish-remains, from Wordley Brook, Abberley: *Auchenaspis Zone* as defined by King (5) (450 feet above L.B.B.).

20*. Purplish, hard, "nodular," micaceous, and slightly calcareous sandstone, with fossils, from Ledbury railway cutting: *Auchenaspis Zone* (450 feet above L.B.B.).

21*. Green and purple, hard, micaceous, and calcareous sandstone, with green marl-pellets, from Wordley, Abberley: *Auchenaspis Zone* (400 feet above L.B.B.).

The following table indicates the percentage composition of the mineral assemblages from the above rocks, the minerals enumerated being zircon, tourmaline, rutile, garnet, staurolite, anatase, apatite, magnetite, leucoxene, ilmenite, and pyroxene:—

	Z.	T.	R.	G.	St.	An.	Ap.	M.	L.I.	Pyr.
					FARLOW SANDSTONE.					
1	44·8	12·3	4·6	—	—	5·3	·1	8·1	24·6	—
2	27·3	2·4	4·9	15·5	—	1·1	10·9	29·0	8·9	—
3	24·3	13·4	7·4	1·6	—	10·5	10·0	3·5	29·3	—
4	40·5	1·4	5·8	3·7	·1	2·3	—	38·1	8·0	·1
5	45·9	1·4	3·6	11·4	—	3·2	4·5	15·9	14·1	—
6	39·8	4·8	5·6	·1	—	17·4	10·9	2·8	18·6	—
7	38·4	4·4	5·3	15·3	—	2·3	5·9	6·4	22·0	—
					DITTONIAN.					
8 }	23·4	·3	2·5	8·3	—	·5	1·2	61·8	2·0	—
8*a* }	20·3	·5	2·3	8·3	—	·5	—	64·8	3·3	—
9	44·6	·3	2·6	17·7	—	·3	·1	29·7	4·7	—
10	26·7	·1	2·8	10·1	—	·3	2·4	56·5	1·1	—
11	20·3	·6	2·3	21·8	—	·3	·5	53·0	1 2	—
12	20·7	·1	2·3	11·5	—	·1	3·3	60·2	1·7	·1
					DOWNTONIAN.					
13	5·7	·6	1·0	80·4	—	·2	2·8	5·3	4·0	—
14	2·3	·1	·7	55·8	·1	—	·3	39·0	1·7	—
15	2·6	·6	·1	56·8	—	—	1·0	37·3	1·6	—
16	8·4	·1	·7	63·5	—	—	·2	27·0	·1	—
17	1·0	·6	·3	93·5	—	·1	·1	4·0	·4	—
18	5·6	2·0	2·2	50·4	·2	·2	·6	37·8	1·0	—
19	1·9	·1	·6	69·1	·1	—	·3	25·9	1·9	—
20	5·3	·6	·6	49·6	—	—	·2	43·1	·6	—
21	9·7	·4	·9	47·3	·2	·1	1·9	38·7	·8	—

For convenience, though obviously open to objection in some ways, approximate averages of the foregoing figures are given, omitting pyroxene.

	Z.	T.	R.	G.	St.	An.	Ap.	M.	L.I.
Farlow Sandstone .	37·3	5·7	5·4	9·5	—	6·0	6·0	14·8	17·9
Dittonian . . .	26·0	·3	2·8	12·9	—	·3	1·2	54·3	2·3
Downtonian . .	4·7	·6	·8	62·9	—	·1	·8	28·7	1·3

The following examples of mineral composition found in some Midland rocks of pre-Devonian age, taken at random, are given for comparison, mainly to emphasize the increase of garnet in the Downtonian beds :—

	Z.	T.	R.	G.	St.	An.	Ap.	M.	L.I.
Cambrian Quartzite, Lickey . . .	79·0	5·6	1·0	·5	—	8·5	—	3·4	2·0
Ordovician Sandstone (green), Soudley, Shropshire . .	63·5	1·9	8·2	5·3	—	3·5	3·0	3·8	10·8
Purple sandstone (same locality) . .	11·7	·4	1·6	1·6	—	·2	—	81·2	3·3
Silurian grit, Church Green, Shropshire .	50·5	1·3	8·0	·5	—	1·7	—	32·3	5·7
Llandovery Sandstone, Rubery . . .	38·2	5·0	·7	·1	·1	·5	—	53·4	2·0

Subsequent to the Old Red Sandstone period, garnet decreases generally in amount through Midland Carboniferous mineral-suites, reaching a minimum in the Enville Conglomerate rocks. A slight increase in the Enville Breccias is followed by a marked one in Bunter Conglomerate times. Such, however, is in no way comparable with the percentage found in the Downtonian, being usually less than 10 per cent, though an exceptional figure of 36·1 has been recorded in a Triassic sandstone near Wombourn in South Staffordshire.

The Relative Frequency of the Chief Constituent Minerals.

The following points must be considered in connexion with the percentage figures. Nos. 2 and 3 were small specimens providing little mineral residue, this probably accounting for their deviation in mineral-content from that shown by the other and adjacent rocks. Besides local concentration of certain minerals, it has frequently been noticed in Midland rocks generally, that the greenish arenaceous beds, though richer in ilmenite, contain much less magnetite than the purplish sandstones, this causing the percentages of the other minerals to depart unduly from the normal (cf. the Ordovician suites given above). Further, for convenience in rapid estimation, distinction is drawn between opaque minerals, magnetite, etc. (dark under reflected light) and the whitish, altered ilmenite grains, owing to difficulty in deciding between magnetite and unaltered ilmenite when counting a large number of grains. Magnetic extraction has shown, however, that most of the opaque iron-ores are magnetite, and that ilmenite, when present, is mostly altered to leucoxene. Lastly, the local absence of apatite may be due to chemical solution and has then little significance, though such affects the percentages of the remaining minerals to some extent. The following are the obvious characteristics connected with the frequency of the various minerals, while it is scarcely necessary to draw attention to the remarkable consistency of the results obtained from such a varied assortment of rock-specimens.

(*a*) The Downtonian rocks are distinguished by an abnormally high garnet-content usually exceeding 50 per cent, and the presence of only small amounts of zircon, tourmaline, rutile, apatite, and leucoxenic ilmenite. Pyroxene was not seen, while staurolite and anatase are exceedingly scarce. Magnetite varies inversely to garnet in amount.

(*b*) The Dittonian rocks are characterized by a reduced, though still high, garnet-content of about 10–20 per cent, with corresponding increases in amount of zircon and magnetite. Tourmaline, apatite, and leucoxenic ilmenite remain much as in the Downtonian, though ilmenite appears to be slightly more frequent. A definite increase in rutile is noticeable. Anatase is slightly more prevalent, but staurolite was not seen, and pyroxene appeared only as a very scarce mineral in one sample. The increase in zircon and diminution of magnetite in No. 9, a greenish sandstone, bears out what has been said above in this connexion, while the close agreement between Nos. 8 and 8*a*, two samples collected by different workers from a fair-sized exposure, is an example of the consistency of the deposits and the results obtained by the methods used.

(*c*) The Farlow Sandstones of the Clee district vary considerably and indicate uneven deposition, the mineral proportions differing considerably in amount within a small vertical range, but as a whole the residues are very different from those of the underlying beds. They are characterized by considerable zircon, titanium-bearing minerals, tourmaline, and apatite. Garnet and magnetite are variable in amount, while staurolite and pyroxene are very scarce.

Two samples of pinkish-purple to greenish-grey hard sandstone, gritty, and with occasional small pebbles of vein-quartz, were obtained from a quarry 2½ miles from Ross on the Monmouth road. Mr. King regards them as belonging to an horizon well above the base of the Farlow Sandstone. Their percentage mineral content is as follows:—

	Z.	T.	R.	G.	St.	An.	Ap.	M.	L.I.	Pyr.
a .	15·4	·4	2·7	46·4	—	·1	1.8	27·3	5·8	—
b .	18·9	·9	3·6	48·1	—	·1	2·7	17·9	6·4	2·3

They show a pronounced resemblance in mineral-composition to the Downtonian rocks as regards garnet percentage, with increases of zircon, rutile, leucoxenic ilmenite, and pyroxene, but are unlike the Upper Old Red Sandstone rocks of the Clee area. Their residues are, in a measure, intermediate in character between Downtonian and Dittonian types.

NOTES ON THE MINERALS.

Attention was mainly directed to the more usually occurring heavy minerals, and therefore the presence and character of quartz, felspars, scarce, and "light" minerals will only be treated briefly.

Quartz.—Secondary silicification of quartz-grains was observed in sample No. 1.

Felspars.—In the examination of residues obtained by " panning ", grains of orthoclase, plagioclase and microcline were observed, particularly in samples from the two lower subdivisions.

Mica.—Muscovite occurs with great abundance in the Downtonian, rather less frequently in the succeeding Dittonian, but is only occasionally evident in the Farlow Sandstone.

Calcite.—Many of the Downtonian and some of the Dittonian samples were markedly calcareous, but calcite was rarely observed in the Farlow Sandstone.

Barytes.—The remarks concerning calcite apply to barytes as regards distribution, but the latter mineral is never present in force like calcite. It occurs as medium or large-sized, clear, angular plates.

Zircon.—Occurs as medium-sized,[1] rounded grains, occasionally rose-pink or purple, but the amount and intensity of colour in the latter are not marked features. A percentage of greenish-yellow, well-rolled forms, reminiscent of similar grains found in Midland Cambrian and Silurian sediments, occurs in the Downtonian.

Tourmaline.—Medium, rarely of large size, worn in appearance and variously coloured from pale yellow or nearly colourless to tawny or smoky-lilac. Quite a number of bluish, semi-transparent forms were noticed in the Farlow Sandstone. A number of good prismatic forms were seen in the Downtonian and worn prisms in the Dittonian and Farlow Sandstones.

Rutile.—In the two lower divisions, rutile is generally of a rich deep amber-yellow colour, but foxy-red to dull crimson grains occur more plentifully in the Farlow Sandstone. Rare geniculate twins occur at various horizons throughout, and an increase in comparatively unworn yellow prisms was seen in the lowest Downtonian.

Garnet.—In the Downtonian and Dittonian rocks this mineral occurs largely as perfectly rolled grains, together with quite angular chips, and there are many grains showing nearly perfect crystal form. It often assumes a large size, but at some horizons the grains are consistently of the same medium size throughout. It is frequently colourless, but there is a large proportion of coloured grains, varying from pinkish-straw to deep brownish-yellow in tint. Dark inclusions are frequent and the grains are often beautifully facetted or of a " watered " appearance, occasionally dusky and partly opaque. In the Farlow Sandstones subangular to rounded grains predominate, and though tinted grains are scarcer,

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[1] The following nomenclature regarding size is used here : —

Approximate diameter of grains	·05–·08 mm. .	small.
	·08–·12 mm. .	medium.
	·12–·2 mm. .	large.
	Larger than ·2 mm. . .	very large.

there appears to be no great difference in type between them and the garnet of the underlying rocks.

Staurolite.—When present, appears as very worn, medium to large-sized, yellow grains in the Downtonian rocks, smaller and more angular in the Farlow Sandstone.

Anatase.—Anatase appears only as small, poor, and detrital forms below the horizon of the Farlow Sandstones, but in the latter it occurs as yellow and dark grains with fair crystalline forms, possibly authigenous, and usually of small size.

Apatite.—Usually as corroded, medium-sized, oval forms, but occasional well-shaped prisms appear throughout, and there is a tendency for smoky or purplish " cored " grains to occur.

Magnetite.—Medium to large in size in the Downtonian and Dittonian rocks, but smaller in the Farlow Sandstone, which, however, occasionally contains a local abundance of good octohedral forms. A few of the latter appear also in the Downtonian. Usually the grains are subangular or rounded in shape.

Ilmenite.—Apart from those grains altered more or less completely to leucoxene, there exists a small proportion of unaltered ilmenite.

Chlorite.—This mineral is fairly abundant in the two lowest divisions, occurring as greenish, oval, and irregular plates.

Pyroxene.—Occurs as medium-sized, sharp, fractured, prismatic grains, smoky-lilac, or pale lavender in tint.

Epidote.—One or two large, deep brownish-yellow, rounded grains were observed in the Downtonian beds.

Glauconite.—This, a " light " mineral, is present in some slides.

SUMMARY AND CONCLUSIONS.

As stated previously the aim of this paper is chiefly to call attention to the differences between the mineral assemblages of the Downtonian, Dittonian, and Farlow Sandstone beds of the Old Red Sandstone, particularly when the percentages of the different mineral grains are obtained by accurate counting. Further work will show how far these investigations may be correlated with the examination of the rocks in adjacent districts, and the author suggests that a similar calculation of percentage figures on the minerals of such deposits may assist in indicating more definitely the sources from which they have been derived.

The following are the chief points of interest arising from a study of the rocks as examined in Shropshire, Herefordshire, and Worcestershire.

1. The Downtonian rocks are characterized by an abnormally high percentage of garnet, with much muscovite, chlorite, and calcite, but only small amounts of other minerals.

2. The Dittonian rocks also show a high garnet-content which, though much less than in the underlying group, is higher than that which usually obtains in other Midland rocks such as the Upper

Carboniferous, "Permian", and Bunter beds. Other minerals such as zircon and magnetite increase considerably in amount, and titanium-bearing minerals are also more prevalent. Chlorite, calcite, and muscovite are plentiful.

3. The Farlow Sandstones of Clee show variation, especially as regards garnet, but exhibit marked increase in zircon, tourmaline, titanium-minerals, and apatite, with reduction of magnetite. Calcite, chlorite, and muscovite are quite subordinate in amount.

4. The abnormally high proportion of garnet in the Downtonian rocks indicates a great influx of fresh material from highly garnetiferous rocks, and is probably connected with the presence of mica and chlorite. The other minerals were probably derived from older sediments, though apatite, a mineral of less stability, may have been freshly derived. Whether the Downtonian garnet, mica, and chlorite came from a pre-Cambrian massif in the direction of Anglesey, following a train of thought suggested by Professor Boswell's remark (6) in a similar connexion, or from quite another source, it seems probable that the scarcity of tourmaline and staurolite indicate that the supply came from rock-sources quite different from those which provided later the garnetiferous and micaceous Bunter Conglomerate of the Midlands, especially since the garnet, staurolite, and tourmaline possess, in Triassic suites, a characteristic appearance distinct from that shown by the same minerals in the Old Red Sandstone.

5. The Dittonian rocks have affinities with the Downtonian in regard to their mineral assemblages. Although the garnet-content is diminished, the percentages of the remaining minerals are maintained, and in the case of some, considerably increased. These facts might be variously interpreted and may imply either derivation as a whole from the Downtonian, partial derivation from those rocks, or a reduced supply from the garnetiferous sources, accompanied in the last two cases with supplies from older sedimentary rocks, possibly lying at no great distance.

[In this connexion it seems that the accurate results obtainable by the procedure described from a given vertical range, may afford information regarding the "life" of certain detrital minerals. In the case of the Downtonian and Dittonian rocks, the consistency of the tourmaline percentage throughout both is certainly striking, when, in the Dittonian, the increase of zircon and magnetite on the one hand, and the diminution of garnet on the other, are so marked. Assuming, for instance, that there was no fresh supply of minerals from external sources in Dittonian times, but only a breaking down of the older Downtonian, one might almost arrive at mathematical conceptions as to the relative durability of garnet, zircon, and tourmaline under the given conditions of erosion deposition and preservation. Partly as a result of the garnet percentage falling from 64·5 to 12·9, zircon increases in percentage amount from 4·6 to 26·0, while tourmaline remains practically stationary, presumably owing to wear and tear nullifying the otherwise expected increase. The above is merely intended to convey, in concrete form, how the data obtainable from a given vertical range might be of use.]

The sharp distinction between Downtonian and Dittonian suites as regards garnet percentage is an outstanding feature, and may be of considerable use in local stratigraphical work.

6. The Farlow Sandstones of Clee, with their distinct mineral suites, indicate a pronounced change in source of material. The considerable increases in tourmaline, apatite, and titanium-bearing minerals are significant items, which when thoroughly understood may well prove of value in appreciating the sequence of events preceding the Carboniferous period.

Generally speaking, the residues indicate that the Farlow Sandstones of Clee were derived from older sediments, other than the Downtonian and Dittonian, without fresh mineral acquisitions in any quantity from igneous and metamorphic rocks. Their relative richness in the minerals enumerated above is perhaps somewhat more apparent than real in consequence of deficiency in magnetite. Allowing for this, the assemblages are not incomparable with such as are found in the Middle and Upper Carboniferous rocks of the Midlands, and which the author considers, on petrological grounds, to have been largely formed from pre-existing sediments. In this respect the increase in foxy-red and crimson rutile is of interest, but staurolite is unusually scarce, while the apatite can hardly be other than freshly derived.

The Upper Old Red Sandstone residues from near Ross indicate that the conditions of deposition *there* may not have been greatly different from those which obtained in Downtonian and Dittonian times in adjacent districts. It is probable that the distinctive suites of the Clee rocks mark a special (? shallow-water) phase of deposition in that area.

In conclusion, much work remains to be done on the rocks under notice here, and till further data are available, wider generalizations are inadvisable. The author would like to express his special indebtedness to Mr. Wickham King, who has rendered possible the above investigation, and his thanks to Mr. S. W. Wooldridge for criticism, particularly in regard to the percentage representation adopted. Mr. E. E. L. Dixon has kindly assisted with criticism at various times.

The author also acknowledges with thanks a grant from the Endowment of Research Fund of the Birmingham Natural History and Philosophical Society towards the cost of the plate illustrating this communication.

The accurate counting of minerals in a residue as an important aid to petrological work was insisted upon by Mr. F. Raw several years ago, but no practicable method was sought till recently, when difficulties encountered in research on Midland sediments rendered the adoption of some such procedure imperative. It may be mentioned that Mr. Wooldridge, following the author's suggestion, has applied the methods described above in connexion with his petrological work on the Lenham Beds (7), and reference to that paper will show how the percentage figures, obtained by actual counting, serve to convey a definite idea of the relative proportions of the various minerals and so permit direct comparisons between the suites of different beds or formations.

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KEY TO PHOTOMICROGRAPHS OF HEAVY RESIDUES.

Plate XXIX.

FIG.

1.—Downtonian Sandstone (Locality No. 17). × 54. Showing abundant garnet, with a little magnetite, and scarce ilmenite, rutile, and tourmaline.

2.—Downtonian Sandstone (Locality No. 16). × 62. Showing abundant garnet, with magnetite and a little zircon.

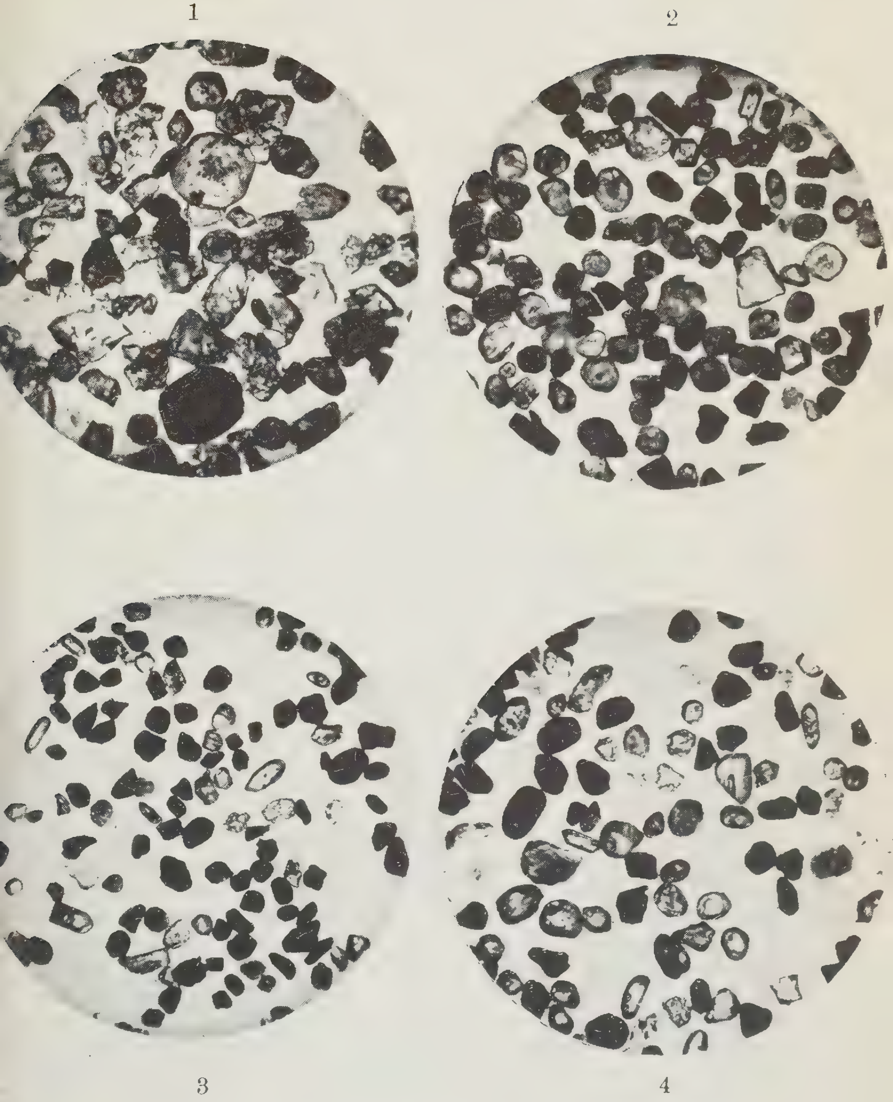
3.—Dittonian Sandstone (Locality No. 9). × 54. Showing magnetite, garnet, and zircon.

4.—Dittonian Sandstone (Locality No. 10). × 62. Showing garnet, magnetite, and zircon, with scarce rutile and brown tourmaline.

The Earth's Thermal History, and Some Related Problems.

By Harold Jeffreys, M.A., D.Sc., F.R.S.

It seems to be curiously difficult to obtain fair treatment for the theory of a continuously cooling earth and its consequence, the thermal contraction theory of mountain formation. After Davison and Darwin had calculated the available compression of the earth's crust on Kelvin's theory of the cooling of the earth, and obtained a result that was at any rate of an order of magnitude consistent with the observations then available, Osmond Fisher



Heavy Minerals of the Old Red Sandstone.

[To face p. 516

made a revised comparison, which amounted to supposing the mountains formed by compression all powdered and spread out uniformly over the whole surface of the earth; the thickness of the resulting layer was naturally very much less than the actual height of known mountains. So far as I have been able to trace, nobody protested against the assumption that the thickness of the material after it had been redistributed in this way was directly comparable with the height of the mountains as actually distributed, and Osmond Fisher's view seems to have been universally quoted as the last word on the subject. Even long after my rediscussion of the whole question [1] in 1916, making allowances for the additional data provided by radioactivity, had again led to a result agreeing with observation within the uncertainty of the data, it was almost completely neglected in the literature of the subject, while Osmond Fisher's work retained undisputed pre-eminence.

The foregoing remarks are largely inspired by Professor A. Holmes's statements [2] that the theory of continuous cooling " has consistently failed to lead to any adequate explanations of fissure eruptions and other volcanic and tension phenomena; mountain-building processes and their distribution in time and space; and the alternation of marine transgressions and recessions ". These alleged failures include what I should have described as the principal successes of the theory. Starting with the known rate of increase of temperature with depth in the crust, and the known radioactivity of surface rocks, Holmes in 1916 showed that the data could be co-ordinated with a single *ad hoc* numerical assumption, corresponding to the rate of decrease of radioactivity with depth. In my further development of the theory I found, without any further assumption, merely by applying laboratory determinations of certain physical quantities, that it implied an amount of crustal compression comparable with that involved in known mountain ranges, a number of eras of mountain formation comparable with that known from geology, and thrusting from the ocean towards the continents such as is required to account for the Pacific type of mountains. I am aware that some geologists have claimed that the estimates of crustal compression I used refer only to comparatively recent mountains, and that in consequence my estimate of the compression may be only half or a third of the amount to be explained; but this criticism does not in the least touch the real issue. My estimate depends on its numerical data, and though all of these are presumably of the correct order of magnitude, some are capable of appreciable alteration. Consequently an agreement in order of magnitude is the most that could be expected; and nobody has asserted that it has not been obtained. Since my last revision of the calculation [3] several reasons for an increase in the theoretical compression have arisen. Evidence has accumulated that the deep-seated rocks, whose cooling mainly determines the compression, are of the nature of olivine rather than basalt, and therefore their melting-point is higher than I supposed. Bridgman's experimental work [1] has shown that the thermal conductivity probably increases somewhat with depth. The discovery of Holmes and Lawson [2] that the radioactivity of potassium is appreciable will necessitate a reduction in the estimated thickness of the granitic layer and therefore an increase in the cooling at great depths. Also contraction due to change of state, though not demonstrated, is a possibility that may have to be considered in the near future. It is impossible to say on present knowledge that the theory implies insufficient compression, and mountains exist in the place where it most definitely leads us to expect them, where the longest straight coast faces a great ocean. It could hardly be expected to account for the distribution of mountains in the interior of continents without some previous clue to the position of the lines of weakness in the primitive continents.

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[1] *Phil. Mag.*, vol. xxxii, 1916, 575–91.

[2] GEOL. MAG., July, 1926, p. 306.

[3] *The Earth*, 1924, chap. x.

It is true that the theory of continuous cooling has not accounted for marine transgression and recession, but it can scarcely be said to have failed. It has not tried. I can only plead in extenuation that I have not been wholly idle in the last ten years, and that nobody else has shown any very effective interest in the theory. But I should like to point out that the theory, as at present developed, has been concerned chiefly with the total compression, and for this purpose it is enough to know the average values of the radioactivity of rocks and the vertical temperature gradient, which are moderately reliable. To explain vertical movements of continental or subcontinental extent we must consider variations of the cooling from place to place, and for this purpose the thermal survey of the earth must be carried out much more completely. The systematic difference between continents and oceans must have led to differential cooling, amounting to something of the order of 300° at a depth of 100 km. The resulting difference of volume contraction would increase the depths of the oceans below the mean continental level by an amount comparable with a kilometre. This would be expected to have accumulated throughout geological time. But in addition the cooling at great depths, while the outer surface remained at much the same temperature throughout the time, would produce a tendency for the crust to bend. In view of the differences between the radioactive contents in different places, and of the variation in the rigidity of the rocks from place to place, this tendency would lead to the depression of some regions below others ; this again turned out to be comparable with a kilometre in the only case so far investigated.[3] When fracture or mountain formation began some of the stresses would be released, and the curvature of the crust would be re-distributed. Some transgression and recession are therefore to be expected on the theory of continuous cooling; but a direct comparison with geological history must await more data.

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[1] *Am. Journ. Sci.*, vol. vii, 1924, pp. 81–102.

[2] *Nature*, 1st May, 1926, pp. 620–1.

[3] *The Earth*, pp. 140–3.

An objection I have heard advanced against Holmes's theory of 1916 and its consequences is that it supposes the radioactive elements concentrated in the upper crust, whereas their high density would lead us to expect them to be more abundant at great depths. It may be replied that density is far from being the only thing that determines vertical distribution; but at present it is not necessary to provide an explanation of the upward concentration. Supposing for the sake of argument that radioactivity throughout the earth was as great as in surface rocks, a simple calculation shows that the total heat being generated internally would make the vertical gradient of temperature some hundreds of times what it actually is, and that fusion temperatures would be reached at a depth less than a kilometre. The rest of the interior would be fluid. There would be no ocean tides, no distortional or long waves from earthquakes, and no strength would be available to support any but the most insignificant hills. It is for those who deny, on *a priori* grounds, that the radioactive elements are concentrated in a surface layer, to decide their own attitude to these consequences of their denial. Accepting the concentration as *a posteriori* necessary, we must determine its degree so as to fit the facts. This is the principle of Holmes's work of 1916, which he has since abandoned on what seem to me quite inadequate grounds.

Of the deficiencies that Holmes now finds in his former work, the only one that seems to me to carry any weight is that it does not explain vulcanism and intrusion. But when a theory with several notable successes to its credit fails to provide an immediate explanation of a single phenomenon it is not necessary to abandon the theory entirely on that ground alone. Astronomers did not abandon the law of gravitation because it did not explain the whole of the motion of the perihelion of Mercury; they remembered that it did account for all the other known phenomena of the motions of the planets and of double stars, and trusted that the difficulty with regard to Mercury would in time be solved without altering the law seriously. Their optimism has been thoroughly justified. The undulatory and the quantum theories of light explain two distinct sets of facts; but physicists do not abandon either, and await a more complete theory that will combine the successes of both. I personally have thought for some years that vulcanism and compression are fundamentally independent phenomena, not attributable to the same cause. I have previously commented[1] on the difference in level between two neighbouring lava lakes in Hawaii as decisive evidence that these lakes cannot be in communication with the same internal source of magma. A similar point is made by Day.[1] The magma must be formed locally, and cannot represent an extensive fused region. Day attributes the fusion to chemical action, and I think his suggestion goes far towards providing an explanation of vulcanism and tension phenomena generally. It is free from the chief defect of any theory that appeals to radioactivity as the source of volcanic heat, that vulcanism once started in this way could never stop, whereas we know of numerous cases where it has stopped. Suppose for instance that a basaltic outflow has begun. It submerges the more radioactive granitic rocks to a greater depth than before. The effect of radioactive material on underground temperatures depends not only on its quantity, but on its depth; the greater the depth of the source of heat, the greater the temperatures attainable. Hence the outflow would increase the temperatures in the layer subject to fusion. It may be difficult, as Holmes suggests, for the magma to reach the surface when it is first formed, but granting the possibility of basaltic outflows at all it would certainly be easier for one to continue than to begin. The great advantage of chemical action as an explanation of volcanic temperatures is that it stops when the supply of active materials is exhausted or blocked up; radioactive heating goes on all the time. The only importance attributable to radioactivity in relation to vulcanism and intrusion is that it keeps the average temperature up, and thereby makes it easier for other sources of heat, which must be local and temporary, to raise the temperature to fusion point.

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[1] *The Earth*, p. 152.

Impossibility of Alternation.

Professor Joly has proposed a thermal history of the earth that claims to explain both compression and tension as alternating phases of the same process. Holmes adopts a similar theory with some modifications. As I have expressed my views on Joly's theory elsewhere,[2] I do not propose to rediscuss the question generally, but only to enunciate my main conclusion: whenever a physical system of finite extent, free to lose heat by radiation from an outer boundary, is affected by a steady internal source of heat, the temperature at any point will approach steadily towards some permanent value as a limit, and there will be no possibility of a permanent oscillation of temperature. So long as the system is solid this proposition can be proved easily; fusion, if it occurs, complicates the mathematics but leaves the result no less evident physically. Joly complicates the issue further by assuming that the entire crust revolves under tidal forces; this introduces the possibility of some oscillation of temperature, but not enough to produce resolidification, and is open to objections on its own account.

Holmes attempts to allow for the possibility of the roof foundering

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[1] *Some Causes of Volcanic Activity*, Franklin Inst., 1924.

[2] *Phil. Mag.* (7), i, 1926, 923–31.

en masse or by crystal stoping. I cannot admit, however, that either of these events would affect the main result. Taking first the case where the material is the same right up to the surface, which is maintained at a constant temperature by radiation (with possibly the ocean as an intermediary) I agree entirely with Mr. MacCarthy.[1] I would only add that if there were a layer capable of being fused by internal heating, it is unlikely that this heating would be uniform, and some cell would fuse first. The roof would collapse on this when it became large enough, and the fluid would be transferred to the top, where it would solidify again, while the solid that took its place, being already nearly at the melting point, would proceed to fuse under the continued heating. The process would therefore be repeated indefinitely. Meanwhile fusion would spread horizontally, and ultimately we should have a continual process of instability convection or turbulence, analogous to what occurs in the boiling of a kettle, the main difference being that the large fractured lumps of solid would play an essential part in the transfer of heat.

An upper layer of a different solid material, light enough to float on the fluid, would prevent the turbulence from extending up to the outer surface, but otherwise the conditions would remain the same; a temperature gradient would be gradually established in the upper layer such as would enable it to conduct away the heat generated below. With either complete foundering of the roof or the more gradual process of crystal stoping the result of fusion would be a statistically steady state, matter solidifying as it rises, then sinking again and fusing on the way down, the intensity of the movement adjusting itself so that convection is able to carry off the new heat as fast as it is supplied—again as in the boiling of a kettle.

To put the matter in another way, it is known that for many purposes turbulence in a fluid can be treated as simply a great increase in the conductivity; while latent heat can be regarded as a great increase of the specific heat over a small range of temperature. Thus the conditions in a partly fluid system should be perfectly represented by those in a heterogeneous solid system.

In any case the onus of proof that the theory of magmatic cycles explains anything at all rests with its supporters, at least if the word "explain" is understood in the sense given to it by most physicists. A theory explains a fact if it starts from a set of stated hypotheses and shows how the fact in question follows from them. But the theory of magmatic cycles considers itself at liberty to use the observed facts to enable it to infer its own consequences; and any fact can be explained on any theory if that is permitted. If resolidification under excess of internal heat is possible it should be well within the experimental powers of both Professor Joly and Professor Holmes to demonstrate it; without this no case for the theory has been made out.

[1] Geol. Mag., July, 1926, 301–5.

THE SYENITE LAYER.

In the course of his paper,[1] Holmes makes the interesting suggestion that the floor of the ocean is covered by a layer of syenite, whose thickness he estimates at 4 to 8 km. The observed values of the group-velocities of Love waves under the oceans, as found by Gutenberg, show an even greater scatter than those found for continental regions, and therefore I should hesitate to lay much stress on the quantitative determination. But the existence of a syenite layer would open up important possibilities about the early history of the earth. There is at present no explanation of the origin of continents that can be regarded as even remotely satisfactory. The concentration of the granitic rocks into a third of the earth's surface could not have taken place while the earth was fluid; equally it can not have taken place since it became solid. The only opportunity for it was during the solidification, which must have taken a finite time. Let us suppose then that during solidification a layer of acidic rock collected on the surface and partly solidified. At this stage the whole would be symmetrical. After a thin shell had solidified it would take a very short time to sink to nearly the present external temperature, contracting meanwhile in such a way as to tend to preserve its symmetry. But in doing so it would become too small to hold the still fluid interior, and it would be torn asunder, probably by a few large cracks, since it is easier to extend an old crack than to start a new one. The fluid interior could then accommodate itself to the size and shape of the shell by flowing out through the cracks. On reaching the outside it would spread out horizontally, but it would be delayed by viscosity and might well have failed to overflow the whole surface before it solidified. Thus the acidic layer might acquire some very thick patches, which would probably be more on one side of the earth than the other. The suggestion requires further examination, but it may be worth while to call attention to the possibility that a thin primitive layer of light rock over the ocean floor may facilitate the explanation of the earth's asymmetry of figure.

THE THICKNESS OF THE GRANITIC LAYER.

It was discovered by A. Mohorovičić in 1909 that near earthquakes sometimes sent out two compressional waves, one of which travelled in an upper layer, which we should now identify with the granitic layer, and the other mainly in a lower one. He used the times of arrival of these waves to determine the velocities of these waves, the depths of the foci, and the thickness of the upper layer; he found the latter to be about 60 km. In this he has been followed by continental seismologists. It is curious that in all discussions of later earthquakes nearly the same depth has been found for the upper layer, whereas appreciably different values have been found for the velocities; a small change in the adopted value of either velocity would lead to a notable change in the depth inferred. Since all these discussions have been made by rather unsatisfactory graphical methods, I have recently rediscussed all the data by the method of least squares; the results, which are awaiting publication by the Royal Astronomical Society, may be of some geological interest. The velocity in the upper layer is 5·6 km./sec., and that in the lower 7·8 km./sec. Both have a mean square error not exceeding 0·1 km./sec. The upper velocity is appropriate to granite. Adams and Gibson find[1] that the velocity in dunite at ordinary temperatures and the pressures corresponding to depths of 0, 40, and 60 km. would be 7·9, 8·2, and 8·4 km./sec. Remembering that the actual velocity within the earth would be somewhat lower on account of the higher temperature, we see that these results are consistent with the lower layer being composed of dunite. The density of the specimen tested was 3·29.

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[1] GEOL. MAG., July, 1926, 306–29.

A wave that presumably travelled through an intermediate layer has been traced in the records of two earthquakes. The times for one of these were well observed, and correspond to a velocity of 6·2 km./sec., with about the same degree of accuracy as was obtained for the other waves; but more observations are clearly desirable. The velocity in gabbro would be about 7·1 km./sec., and that in a basaltic glass, according to Adams and Gibson, would be 6·4 km./sec. The elastic properties of eclogite have not been experimentally determined. The data, so far as they go, would fit an intermediate layer of basaltic glass.

The determination of the depths of the layers is less satisfactory. The foci were in all cases in the upper layer and in no case was more than one station near enough to be useful in finding the focal depth. The consistency of the observations among themselves is not enough to determine the depth of the focus or the increase of the velocity in the upper layer with depth. These uncertainties are reflected in the determination of the thicknesses of the layers, which have to be found by comparing the times of arrival of the different waves. The data would be consistent with a thickness of 12 km. for the granite layer and 20 km. for the basalt layer, but both are subject to accidental errors of about 4 km. and to systematic errors of quite unknown amount.

There is some reason to believe that both the transitions are continuous. If they were sudden waves would be reflected from them, and Heidelberg and Jugenheim were both excellently placed to observe such waves from the Oppau explosion had they existed. Though some indirect waves were recorded, it does not seem possible to interpret them as waves reflected at horizontal interfaces; any such interpretation leads to a contradiction.

If we regard the difference of mean level between the continents and the oceans as due to the balancing of a column of granite by one of dunite, the thickness of the granite layer should be about 16 km. Holmes's method of 1916 leads to about the same result, if the radioactivity of the lower layers be ignored. My result based on Love waves was about 15 km. All of these require some correction to allow for the basalt layer, but they are in good enough agreement to suggest that we are on the right track.

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[1] *Proc. Nat. Acad. Sci.*, xii, 1926, 275–83.

THE UPWARD CONCENTRATION OF RADIOACTIVE MATTER.

Holmes has already suggested[1] that the concentrating action of volatile compounds may have been of importance in raising the radioactive elements to the outside. In view of some recent work this hypothesis has considerable claims to acceptance. It has been pointed out by Aston that the inert gases play an extraordinarily small part in the percentage constitution of the earth as a whole.[2] This is explicable if we suppose that the primitive fluid earth was too hot to retain an extensive atmosphere. The inert gases, having no possible resting place except in the atmosphere, would escape from the earth's influence. So would more active gases that could not readily form compounds or solutions able to retain them at magmatic temperatures. It is significant in this connexion that rock analyses show an amount of oxygen almost exactly enough to combine with all the other constituents. The present ocean and atmosphere must then have originally been entirely contained within the primitive magma. We should then expect the water to have been originally fairly uniformly distributed in the rocky shell, and to have been extruded from it during solidification. But this solidification must have taken place at a temperature far above the critical temperature of water, so that the separation of the water would involve a process of steam distillation on a gigantic scale. Any compounds volatile at magmatic temperatures would therefore be carried up to the top. Now uranium forms a hexafluoride, which sublimes at 55° at atmospheric pressure, and a tetrachloride volatile at a red heat, while the compound UO_2F_2 on heating in certain conditions[3] gives a sublimate of UO_2. Thorium tetrachloride has been sublimed at a high temperature; the tetrafluoride melts at 820°, but I can trace no record of its volatility.[4] Some of these compounds would be partly hydrolysed in presence of steam, but the fact that they would be removed as fast as they were formed would enable the process to be completed with some delay in time, just as the volatility of hydrochloric acid makes it possible to complete the conversion of sodium chloride into sulphate by means of sulphuric acid.

The analyses of Pre-Cambrian granites quoted by Holmes support this tendency of radioactive matter to collect in the upper layers when the rock is fused. If then the distribution were such as to lead to fusion, the radioactive matter would begin to move upwards; and this movement would continue as long as the rock remained fluid. But when the upward concentration had reached a certain amount the heating would be reduced to such an extent that fluidity could no longer be maintained. On this ground alone it seems that ultimate general solidification would be inevitable (apart as before from temporary sources of heat not due to radioactivity). Now on this point I think the present state of the moon serves as a useful illustration. If the moon were formed from the earth it must have been formed mainly from the outer parts, and therefore must have an undue proportion of granite. It is not difficult to see that its granite layer would be thicker than that of the earth absolutely as well as relatively. Consequently it may have been originally heated up continuously by radioactivity until an extensive system of volcanic features was formed; but the subsequent upward concentration would put an end to this process, leaving the moon in a nearly steady thermal state. This would explain why the moon is now completely quiescent in spite of its riotous youth.

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[1] GEOL. MAG., February, 1915.

[2] *Nature*, 29th November, 1924, p. 786.

[3] Smithells, *Journ. Chem. Soc.*, xliii, 1883, 128.

[4] Duboin, *Ann. d. Chimie* (8), xvii, 356, 1909.

REVIEWS.

THE PROBLEM OF GEOLOGICAL TIME. Estimates of Geological Time, with special reference to Thorium Minerals and Uranium Haloes. By ARTHUR HOLMES. *Phil. Mag.*, May, 1926, pp. 1055–74.

IN recent years Professor J. Joly has steadily attacked the validity of the longer estimates of geological time which have been calculated from the lead-ratios of radioactive minerals. His reasons for preferring shorter estimates have been based on the solvent denudation method; on the fact that thorium minerals often give lower ages than uranium minerals of the same geological period; and on the results of his own remarkable work on pleochroic haloes, results which suggested to him that uranium disintegrated more rapidly in former ages than it does now owing to the wearing out of a hitherto undiscovered isotope of that element.

Lord Rayleigh and Dr. Holmes were the pioneers in this country of the application of the principles of radioactivity to the problem of geological time. Dr. Holmes has never wavered in his advocacy of the longer estimates, and now, in this important paper, he gives the reasons for his faith. The sodium method is rejected on the grounds that the rocks would have to lose more sodium than they had ever contained in order to supply the amounts alleged to be newly added each year to the ocean; and further that the assumption of uniformity of rate is far from justified. Both criticisms lead to the conclusion that the method cannot be considered to make any serious contribution to the problem. For a fuller account of the flaws in this method, see *Nature*, 24th April, 1926, p. 592. Turning next to the vexed question of thorium minerals, Dr. Holmes shows that if uranium disintegrated more rapidly in the past, then for a suite of thorium minerals of given geological age there should be a regular relation between the lead-ratios and the ratio of thorium to uranium. The actual variation is quite irregular. Some thorium minerals give the same ratios as uranium minerals, but others give ratios that are very low. Joly has picked out the lowest as being likely to be most correct, and has ignored the remaining evidence. Dr. Holmes explains all the discrepancies of thorium minerals by the hypothesis that the lead produced in the latter is most likely to be present as oxide or silicate, while that generated in an environment of uranium and oxygen is most likely to be present as a highly insoluble uranate. Percolating waters and kinetic exchange within the crystals would then leach lead out of thorium minerals, thus making them unreliable as age indices, very much more readily than out of uranium minerals, which are chemically less liable to external interference. An analysis of atomic weight determinations on lead from thorium minerals consistently supports this view, and points, moreover, to the conclusion that uranium cannot have disintegrated in the past at a rate more than a few per cent higher than the present rate. This evidence answers in advance a suggestion by Mr. T. R. Wilkins (*Nature*, 22nd May, 1926, p. 720) that a variable fraction—up to 40 per cent—of " uranium lead " may be Actinium D. In that case a varying atomic weight should be found ; but, as Dr. Holmes's data show, the actual variation, if any, is in the wrong direction.

The deduction drawn by Joly from the varying radii of pleochroic haloes is then shown to be only one, and that the least probable, of several other possible explanations. One conjecture involves the possibility that an isotope of shorter life than uranium was formerly more abundant than now, but it is shown that so far from making 300 per cent difference in the age estimates, as Joly has suggested, it cannot make more than a 3 per cent difference. Mr. Wilkins also ascribes the pleochroic halo anomalies to an isotope of uranium, and claims a 40 per cent difference, but, as stated above, the atomic weight evidence does not support his speculation.

It will be interesting to see what reply Professor Joly can make to this sweeping criticism of his recent addresses and writings on the subject of geological time. The next few months should see the relation of actinium to uranium revealed, and that, whatever it prove to be, will definitely settle the outstanding problems. Meanwhile it is at least safe to say that most of the discrepancies that have been responsible for an age-long controversy are at last being satisfactorily explained, and before long the Aberdonians should no longer be able to say, as after a famous B.A. meeting, " they haven't settled it yet."

A MANUAL OF RADIOACTIVITY. By G. HEVESY and F. PANETH, translated by R. W. LAWSON. pp. xix + 252, with 42 figures. Oxford University Press, 1926. Price 15*s*.

THE greater part of this book is naturally intended purely for physicists, but Chapter xxvi is entitled " Radioactivity in Geology and Geophysics ". It only amounts to about ten pages, but should be useful to geologists, as giving a brief and authoritative account of the latest developments of a subject which has played so large a part in geological speculation in the last few years. This chapter deals mainly with the determination of the age of minerals from the lead-ratio and from pleochroic haloes, the distribution of radioactive substances and its thermal consequences, and the bearing of radioactivity on meteorology and climate. The bibliography attached to this chapter is useful, but is apparently not quite up to date.

ON THE BLAKE COLLECTION OF AMMONITES FROM KACHH, INDIA. By L. F. SPATH. Palaeontologica Indica, N.S., vol. ix, Mem. No. 1, 1924.

THIS memoir deals fundamentally with a large Callovian to Kimmeridgian and a small Aptian collection from Kachh (India) but is of more general interest in its broad treatment of certain Upper Jurassic Ammonoid families. The Kachh beds are correlated, though somewhat provisionally, with the European zones ; and stress is laid on the incompleteness of the succession, the most notable gap being, perhaps, the absence of the Portlandian. References are made throughout to the correlation of Upper Jurassic horizons elsewhere in the Indo-Pacific region. Generic nomenclature is revised by the erection of a number of new genera, the restriction of many old names, and the somewhat more comprehensive use of many genera (e.g. *Macrocephalites*) which have lately been restricted by other authors. The memoir, which deals with many new types (stated to agree with certain of Waagen's figures) is, unfortunately, not illustrated. It is to be hoped that the necessary figures will be given in the author's forthcoming revision of Waagen's types.

General topics discussed include the morphic basis of many families (e.g. *Hoplitidae*) as used at present ; the difficulty of comparing " boreal " and southern faunas ; the unsatisfactory use of such terms as " the Klaus beds " of the Alps ; and the author's objection to the Hyatt-Buckman scheme of ammonite phylogeny.

The work is an exceedingly valuable contribution to the palaeontology of the Upper Jurassic, whose cephalopods have only lately attracted systematic treatment.

F. W. W.

GEOLOGY APPLIED TO MINING. By J. E. SPURR. 2nd edition, pp. xxxii + 361, with 124 illustrations. New York and London: McGraw-Hill Book Co., Inc., 1926.

THE author of this book is well known as one of the foremost mining geologists of the United States, and as editor of the *Engineering and Mining Journal.* In this small book he sets forth in an attractive and readable form the results of his life-long study of ore-deposits in all their relations to general geology. Twenty years ago Mr. Spurr put forward some generalizations on the zonary sequence of ores which, if slow in acceptance, may now be regarded as fundamental in that branch of the subject, and in 1923, in that epoch-making work, *The Ore Magmas,* he expounded his considered views on the magmatic, intrusive origin of the greater number of the workable metalliferous deposits of the world.

In this book are set forth in an admirably lucid manner the general principles of geology as applicable to the needs of the practical mining man. The language is clear and simple, as all true science ought to be, and as the best of American science conspicuously is. Whoso reads this book should at least attain to a knowledge of what geology means, when stripped of palaeontological verbiage and the eccentricities of the arm-chair specialist. It is distinctly an outdoor book, illustrated by reference to a vast number of actual examples, most of them obviously drawn from the author's personal experience, mainly but not exclusively American. A careful study of it can be strongly recommended to all students of mining geology.

CORRESPONDENCE.

THE YOUNGEST BEDS OF NIGERIA.

SIR,—Since the notes "On the Youngest Beds of the Southern Province of Nigeria" (GEOL. MAG., August, 1926, p. 350) were written, "The Geology of the Eastern Railway, Section I", has appeared (*Geol. Surv. Nigeria,* 1925, Bull. 8, p. 51) and contains a mass of information by Capt. Wilson and Mr. Bain. The Lignite Group as developed between Port Harcourt and Enugu is an essentially argillaceous series, the beds passed through in the wells essentially sandy and the correlation accordingly fails in an important point.

The presence of pebbles in both wells, the coarse sand, the plant fragments, black clays with sandy partings (Jamoa, 315–25 ft.) and subordinate black, grey and brown clays suggest rather the Pebbly Sandstone of the Survey Report.

Copies of the logs have been sent to Dr. Falconer.

It should have been stated that both wells were commenced at sea level.

JOHN PARKINSON.